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A new Pliocene biostratigraphy for the northeastern North Atlantic

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With 5 figures and 3 tables

Abstract. This study has aimed to integrate and improve upon the existing marine biostratigraphic schemes pertaining to the Lower to mid-Pliocene (ca. 5.3–2.4 Ma) in the northeastern North Atlantic ('Nordic Atlantic') region. This has been achieved through: the updating of age calibrations for key microfossil bioevents, identification of new events, and integration of new biostratigraphic data from a foraminiferal analysis of cored wells and outcrops in the North Sea region. At these high latitudes, where standard zonal markers are often absent, integration of microfossil groups significantly improves temporal resolution. A new multi-group microfossil zonation is presented comprising 7 Nordic Pliocene (NP) Zones. Zonal duration ranges from 300,000 to 600,000 years. A total of 51 bioevents (28 foraminifers and bolboforms; 17 dinoflagellate cysts and acritarchs; 6 marine diatoms) facilitates zonal identification throughout the Nordic Atlantic region. Via correlations to the bio-magnetostratigraphy and oxygen isotope records of Ocean Drilling Program and Deep Sea Drilling Project Sites, the ages of shallower North Sea deposits have been better constrained. The Early to Mid-Pliocene is biostratigraphically characteristic in being the last time a significant influx of a temperate to subtropical planktonic foraminiferal fauna and dinoflagellate flora was present at such high latitudes in the Nordic and North Seas.

Key words. North Sea, Norwegian Sea, Foraminifera, dinoflagellate cysts, Pliocene, calibrations

1. Introduction

This study aims to improve the temporal resolution and accuracy of the established Lower to Mid-Pliocene (ca. 5.3–2.6 Ma) marine biostratigraphy of the northeastern North Atlantic region. Based on available study material and to maximise the industrial and research application of this relative dating tool, there has been a special emphasis on the North Sea. Since the Neogene deposits of the North Sea and adjoining Nordic Seas have been generally afforded little attention by the petroleum industry, high-resolution integrated stratigraphic data sets are rare. Here economic constraints have limited both quality of material and the availability of paleomagnetic and isotopic data for independent age control. For the late Neogene time interval biostratigraphers have therefore had to rely upon long distance correlations between the neritic North Sea deposits and the well-constrained deep water stratigraphies of the the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP). Extra-basinal correlation to these high-resolution stratigra-

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phies, in particular to the northeastern Atlantic sites, has been the main foundation for biostratigraphic age interpretations and zonation schemes in the North Sea (Eidvin et al. 2000, Gradstein and Backstrom 1996, King 1989, Louwye et al. 2004). In producing a better constrained biostratigraphy for the North and Nordic Seas this study therefore uses the concept of the "Nordic Atlantic Region". This is defined as the region stretching from immediately south of the Greenland-Scotland Ridge northwards, encompassing the North Sea and Nordic Seas (Norwegian Sea, Greenland Sea, Iceland Sea, West Barents Sea) to the Arctic Ocean Gateway and the Yermak Plateau (Fig. 1). This region encompasses a range of deep water Ocean Drilling sites with well-constrained Pliocene stratigraphies, together with a small number of onshore Pliocene outcrops. The rare addition of two Pliocene industrial cored intervals from the northern North Sea (Sleipner and Visund fields) is a result of the Saline Aquifer CO2 Storage project (SACS). The collection of these cores and outcrops form the calibration points upon which this study is based (Fig. 1).

The separation here of the Early to mid-Pliocene period from the preceding Late Miocene and succeeding Late Pliocene is due mainly to the unique paleoclimatologic and paleoceanographic events bracketing this time interval. These being the preceding re-inundation of the Mediterranean and related global sea-level rise (Krijgsman et al. 1999), and the succeeding final onset and main inception of Northern Hemisphere Glaciation (NHG) in Northwest Europe (Haug and Tiedemann 1998, Mudelsee and Raymo 2005). Due to the erosive nature of these bracketing events, especially in the shallow epeiric North Sea, their stratigraphic manifestation is often that of a depositional hiatus. As a result, this pre-NHG Early to mid-Pliocene period has a unique biostratigraphic fingerprint, both in its nature and composition. Mineralogically there is a considerably better degree of carbonate preservation and a higher carbonate con-

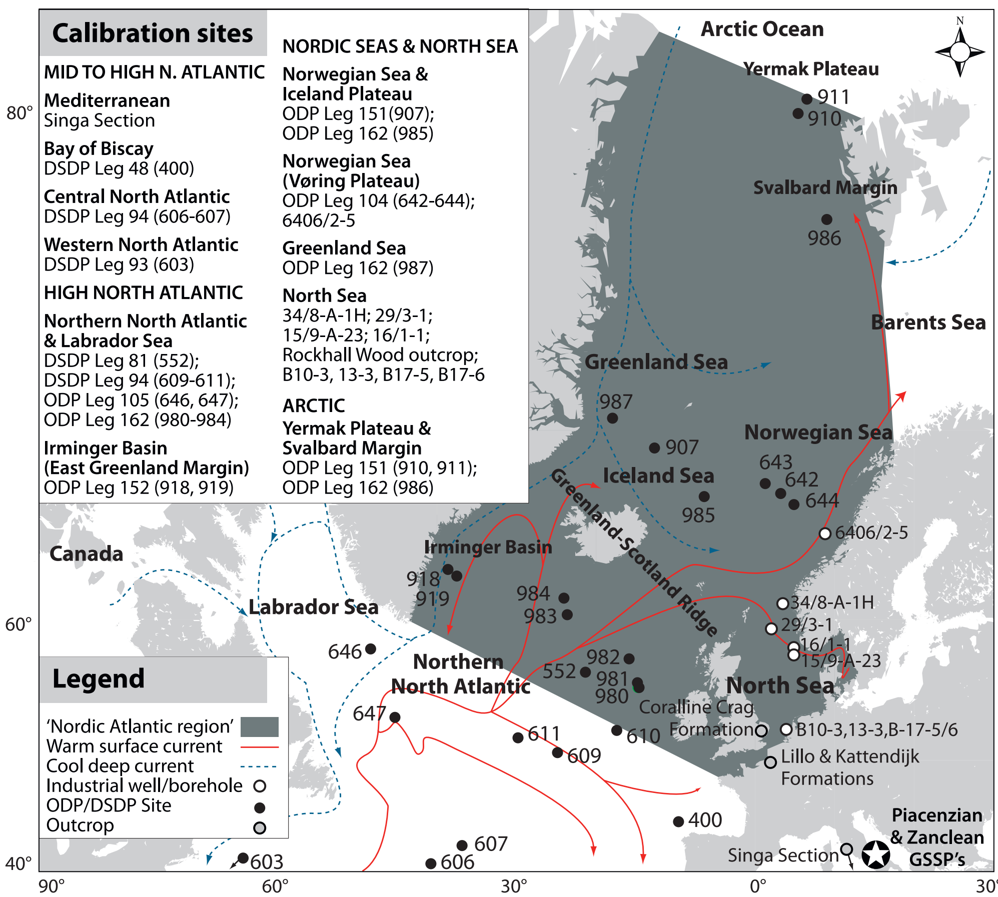


Fig. 1. Location of calibration sites used in constraining the ages of Nordic Pliocene microfossil markers. The 'Nordic Atlantic Region' is highlighted.

tent in Lower to mid-Pliocene sediments of the Norwegian Sea than those from the succeeding glacial period (Henrich et al. 2002). Faunistically, the Early to mid-Pliocene is characteristic in being the last time a significant influx of a temperate to subtropical planktonic foraminiferal fauna was present at extreme high latitudes in the North and Nordic Seas (Spiegler 1996). The much briefer interglacial influxes of temperate foraminiferal species during the Pleistocene, especially during marine isotope stages (MIS) 19 and 5 (Spezzaferri 1998, Anthonissen 2008), cannot be mistaken for the subtropical foraminiferal faunas and thermophilic dinoflagellate cyst floras so characteristic for mid-Pliocene deposits in the North Sea (Hodgson and Funnell 1987, Head 1997, Louwye et al. 2004).

The Early to mid-Pliocene time period is here equivalent to the standard Zanclean and Piacenzian Stages (GSSP's in Van Couvering et al. 2000 and Castradori et al. 1998 respectively). This study uses the terms "Early to mid-Pliocene" instead of "Zanclean and Piacenzian" due to the standard stage boundary markers often being absent or rare at Nordic high latitudes (Anthonissen 2008). Definition of the relevant chronostratigraphic units, i. e. Zanclean, Piacenzian, Pliocene Series and Neogene System follows the current status quo as described in Figures 14.4 and 15.6 of Ogg et al. (2008). The orbitally tuned time scale in this study is that of Lourens et al. (2004), who also re-calibrated the Berggren et al. (1995) biochronology.

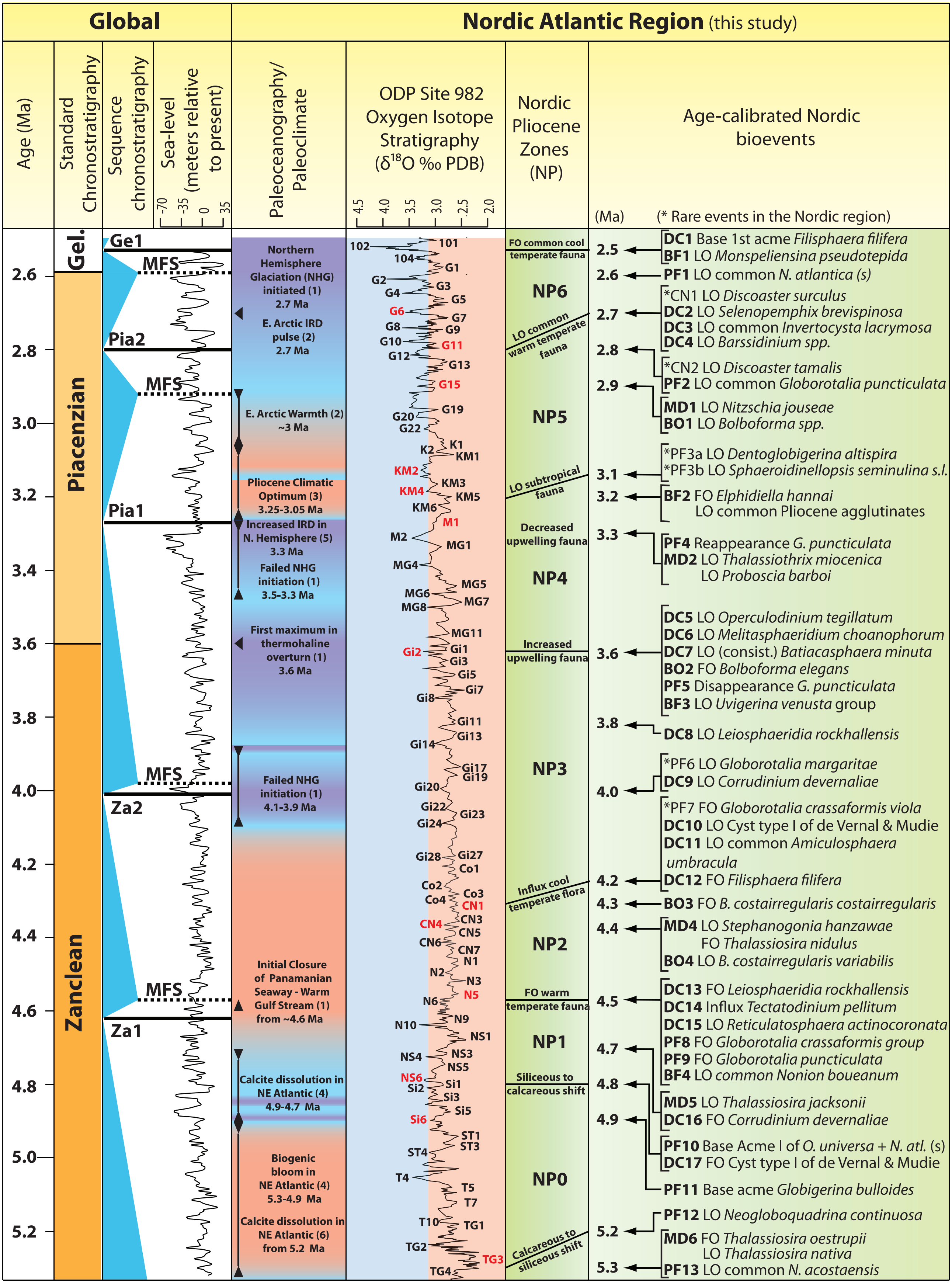
2. Regional setting and biostratigraphy

The 'Nordic Atlantic region' is shown in its geographical and oceanographic context in Fig. 1. In this region the Upper Cenozoic biostratigraphy is based primarily upon foraminifers, calcareous nannoplankton and dinoflagellate cysts. Marine diatoms and bolboformid calcareous algae add paleontological age-control across discrete time intervals. Whereas a number of the standard 'global' markers present in the Mediterranean and mid- to low-latitudes are absent, mid-Pliocene warming resulted in a far greater number of lower latitude taxa making their way to the extreme high latitudes than in the Late Pliocene and Pleistocene (Anthonissen 2008). These include most of the primary and secondary correlative events defining the relevant GSSP's.

3.1 Materials and Methods: mid- to high-latitude regional correlations and calibrations

The location of Nordic ocean drilling sites, cored wells and outcrops analysed, together with selected industrial petroleum wells with well-constrained Pliocene records is shown in Fig. 1. To obtain a new calibrated framework of biostratigraphic events for the Nordic Atlantic region, a four-step method was followed:

1. **Identification of bioevents:** Calcareous, organic-walled and siliceous microfossil bioevents for the Lower to mid-Pliocene were identified primarily in the Ocean Drilling publications of the North Atlantic region. These were either published as is or identified as new events in their respective publications (e. g. the Pliocene planktonic foraminiferal acme events in Fig. 3.)
2. **Updating original age models:** Where available, more recent published data was used to update the original site age models to the Geologic Time Scale of Gradstein et al. (2004). The first main source for the calibrated ages presented here is first-order calibration to the benthic oxygen isotope records of ODP Site 982 and ODP Site 981 and DSDP Site 552A. The oxygen isotope record for Site 982 (Fig. 2) was generated from a composite of the following studies: 5.3–4.6 Ma = orbitally-tuned record of Hodell et al. (2001); 4.6–3.6 Ma = Lisiecki and Raymo (2005); 3.6–2.0 Ma = Mudelsee and Raymo (2005, 2007). Marine isotope stage durations are according to the global stack of Lisiecki and Raymo (2005). The oxygen isotope record for Site 981 is according to Draut et al. (2003) (3.2–3.3 Ma). The oxygen isotope record for Site 552A is according to Keigwin et al. (1987). Based on this raw data and through comparison with the global stack, the individual isotope stages at these four sites were identified. Marine isotope stage durations were taken according to Lisiecki and Raymo (2005). The construction of this Pliocene record is the basis for the dating of the high-resolution record of planktonic foraminiferal acmes/paracmes on the Rockall Plateau (Fig. 3). Identification of these planktonic foraminiferal acmes and paracmes was based on the range charts in Flower (1999). This well calibrated planktonic foraminiferal record was then used to calibrate the shallower benthic foraminiferal record of the North Sea. The second main source for the calibrated ages is first-order magnetostratigraphic control at the respective sites (Bleil 1989, Canninga et al. 1987, Channell



Global
Nordic Atlantic Region (this study)
Age (Ma)
Standard Chronostratigraphy
Sequence chronostratigraphy
Sea-level (meters relative to present)
-70 -35 0 35
Paleoceanography/ Paleoclimate
ODP Site 982 Oxygen Isotope Stratigraphy (δ18O ‰ PDB)
4.5 4.0 3.5 3.0 2.5 2.0
Nordic Pliocene Zones (NP)
Age-calibrated Nordic bioevents
(Ma)
(* Rare events in the Nordic region)
2.6 2.8 3.0 3.2 3.4 3.6 3.8 4.0 4.2 4.4 4.6 4.8 5.0 5.2
Gel.
Piacenzian
Zanclean
Ge1
MFS
Pia2
MFS
Pia1
MFS
Za2
MFS
Za1
Northern Hemisphere Glaciation (NHG) initiated (1) 2.7 Ma
E. Arctic IRD pulse (2) 2.7 Ma
E. Arctic Warmth (2) ~3 Ma
Pliocene Climatic Optimum (3) 3.25-3.05 Ma
Increased IRD in N. Hemisphere (5) 3.3 Ma
Failed NHG initiation (1) 3.5-3.3 Ma
First maximum in thermohaline overturn (1) 3.6 Ma
Failed NHG initiation (1) 4.1-3.9 Ma
Initial Closure of Panamanian Seaway - Warm Gulf Stream (1) from ~4.6 Ma
Calcite dissolution in NE Atlantic (4) 4.9-4.7 Ma
Biogenic bloom in NE Atlantic (4) 5.3-4.9 Ma
Calcite dissolution in NE Atlantic (6) from 5.2 Ma
102 101 104 G1 G2 G3 G4 G5 G6 G7 G8 G9 G10 G11 G12 G13 G15 G19 G20 G22 K2 K1 KM1 KM2 KM3 KM4 KM5 KM6 M1 M2 MG1 MG4 MG5 MG6 MG7 MG8 MG11 Gi1 Gi2 Gi3 Gi5 Gi7 Gi8 Gi11 Gi13 Gi14 Gi17 Gi19 Gi20 Gi22 Gi23 Gi24 Gi27 Gi28 Co1 Co2 Co3 Co4 CN1 CN3 CN4 CN5 CN6 CN7 N1 N2 N3 N5 N6 N9 N10 NS1 NS3 NS4 NS5 NS6 Si1 Si2 Si3 Si5 Si6 ST1 ST3 ST4 T4 T5 T7 T10 TG1 TG2 TG3 TG4
FO common cool temperate fauna
NP6
LO common warm temperate fauna
NP5
LO subtropical fauna
Decreased upwelling fauna
NP4
Increased upwelling fauna
NP3
Influx cool temperate flora
NP2
FO warm temperate fauna
NP1
Siliceous to calcareous shift
NP0
Calcareous to siliceous shift
2.5 DC1 Base 1st acme Filisphaera filifera
BF1 LO Monspeliensina pseudotepida
2.6 PF1 LO common N. atlantica (s)
*CN1 LO Discoaster surculus
2.7 DC2 LO Selenopemphix brevispinosa
DC3 LO common Invertocysta lacrymosa
DC4 LO Barssidinium spp.
2.8 *CN2 LO Discoaster tamalis
2.9 PF2 LO common Globorotalia puncticulata
MD1 LO Nitzschia jouseae
BO1 LO Bolboforma spp.
*PF3a LO Dentoglobigerina altispira
3.1 *PF3b LO Sphaeroidinellopsis seminulina s.l.
3.2 BF2 FO Elphidiella hannai
LO common Pliocene agglutinates
3.3 PF4 Reappearance G. puncticulata
MD2 LO Thalassiothrix miocenica
LO Proboscia barboi
DC5 LO Operculodinium tegillatum
DC6 LO Melitasphaeridium choanophorum
3.6 DC7 LO (consist.) Batiacasphaera minuta
BO2 FO Bolboforma elegans
PF5 Disappearance G. puncticulata
BF3 LO Uvigerina venusta group
3.8 DC8 LO Leiosphaeridia rockhallensis
*PF6 LO Globorotalia margaritae
4.0 DC9 LO Corrudinium devernaliae
*PF7 FO Globorotalia crassaformis viola
DC10 LO Cyst type I of de Vernal & Mudie
DC11 LO common Amiculosphaera umbracula
4.2 DC12 FO Filisphaera filifera
4.3 BO3 FO B. costairregularis costairregularis
4.4 MD4 LO Stephanogonia hanzawae
FO Thalassiosira nidulus
BO4 LO B. costairregularis variabilis
DC13 FO Leiosphaeridia rockhallensis
4.5 DC14 Influx Tectatodinium pellitum
DC15 LO Reticulatosphaera actinocoronata
4.7 PF8 FO Globorotalia crassaformis group
PF9 FO Globorotalia puncticulata
4.8 BF4 LO common Nonion boueanum
MD5 LO Thalassiosira jacksonii
4.9 DC16 FO Corrudinium devernaliae
PF10 Base Acme I of O. universa + N. atl. (s)
DC17 FO Cyst type I of de Vernal & Mudie
PF11 Base acme Globigerina bulloides
PF12 LO Neogloboquadrina continuosa
5.2 MD6 FO Thalassiosira oestrupii
LO Thalassiosira nativa
5.3 PF13 LO common N. acostaensis

et al. 1999a, Channell and Lehman 1999, Channell et al. 1999b, Clement and Robinson 1986, Clement et al. 1989, Fukuma 1998, Hailwood 1979, Keigwin et al. 1987, Krumsiek and Roberts 1984, Shipboard Scientific Party 1995). Ages have been updated to the Astronomically Tuned Neogene Time Scale (ATNTS) of Lourens et al. 2004.

3. **Calculation of calibrated bioevent ages:** Bioevent ages have been calculated via linear interpolation from updated age models. Interpolated ages have been calculated based on their relative positions between bracketing levels. These bracketing levels (or age model tie-points) are magnetosubchron, standard nannofossil zone and/or MIS boundaries. In some cases, a calibration point (i. e. within a magnetosubchron, nannofossil zone or MIS Stage) was observed directly at the same stratigraphic level as the bioevent – an 'observed calibration point' (e. g. 'bioevent x' was observed at the same level as an identification of magnetosubchron y') . In other cases the calculated age allowed for an indirect inference of an 'equivalent calibration point' (e. g. 'bioevent x' was observed at a level with a calculated age equivalent to a placement within magnetosubchron y'). Equivalent calibration points are always shown preceded by an "=" sign (See Appendix 1).

4. **Regional comparison of calibrated ages:** So as to identify possible latitudinal trends, the resulting calibrated ages were arranged according to latitudinal regions defined roughly as: 35°–50° N mid- to high-latitude North Atlantic; 50°–63° N high-latitude North Atlantic; 63°–70° N Nordic Seas and North Sea; 70°–80° N Arctic. The entire area discussed in this study (Fig. 1) has the Mediterranean at its southern limit and the Arctic Ocean at its northern limit. The choice of these latitudinal regions was based on the Pliocene planktonic foraminiferal assemblage distributions of Thunell and Belyea (1982) as follows: 35°–50° N = Mediterranean latitude and southernmost calibration sites to the northernmost dominance of the "Tropical-Subtropical Zone"; 50°–63° N = northernmost dominance of the "Tropical-Subtropical Zone" northwards to the southernmost dominance of the "Polar-Subpolar Zone"; 63°–70° N = southernmost dominance of the "Polar-Subpolar Zone" northwards to the southernmost junction between the Norwegian Sea and Barents Sea; 70°–80° N = Barents Sea to Yermak Plateau (Arctic Ocean). The resulting 145 calibrated bioevent ages were then averaged on a per region basis, taking into account possible reworking and contamination signals (Appendix 1). Where contrasting ages exist for an event in a single region, the most reliable calibration was used (see below).

5. **Sources of error:** For the majority of events the age has been calculated at the depth originally quoted in the respective ODP publications, taking into account any non-continuous sampling. Biostratigraphic sampling resolution can account for the greatest uncertainty in the stratigraphic position of an event. Interpolation uncertainty arises due to uncertainty in the depths and/or ages of the bracketing age model tie-points (e. g. magnetic reversal boundaries). The 'interpolation interval' used to calculate a bioevent age is the stratigraphic spacing in depth and time between the bracketing age model tie-points. The smaller the interpolation interval, the more reliable the interpolation. This is due to the calculation of average sedimentation rate over a shorter interval being more precise than over a longer interval. Therefore, assuming the effects of biological and mechanical reworking of the fossil record to be minimal, the most reliable calibration site for a bioevent is the one with the highest biostratigraphic sampling resolution and the smallest interpolation interval. Due to this inherent uncertainty, indi-

Fig. 2. A new multi-group Nordic Pliocene Zonation for the Lower to Mid-Pliocene of the northeastern North Atlantic region. Standard chronostratigraphy follows the time scale of Gradstein et al. (2004). Sequence chronostratigraphy is according to Hardenbol et al. (1998) with the updated ages of Ogg and Lugowski (TSCreator 2008). The global sea-level curve is according to the software 'TimeScale Creator Pro'. Paleoceanography and paleoclimate according to: 1. Haug and Tiedemann (1998); 2. Knies et al. (2002); 3. Mudelsee and Raymo (2005); 4. Diester-Haass et al. (2005); 5. Fronval and Jansen (1996); 6. Hooper and Weaver (1987). The raw oxygen isotope data for Site 982 is a composite of the following studies: 5.3–4.6 Ma = Hodell et al. (2001); 4.6–3.6 Ma = Lisiecki and Raymo (2005); 3.6–2.0 Ma = Mudelsee and Raymo (2007). Isotope stages have been interpreted based on comparison with the global stack of Lisiecki and Raymo (2005). Those highlighted in red have been identified as coinciding with individual bioevents (See Table 2; Appendix 1). The warm to cold (red to purple) paleoclimate record is an interpretation based on comparison with the oxygen isotope record and record of planktonic foraminiferal acmes on the Rockall Plateau (See Fig. 3). Correlation of bioevents to the marine oxygen isotope record and paleoceanographic/paleoclimatic trends is based on the new and updated age calibrations in this study. Bioevent codes: CN = Calcareous Nannofossil; PF = Planktonic Foraminifera; BF = Benthic Foraminifera; BO = Bolboforma; DC = Dinoflagellate cyst or acritarch.

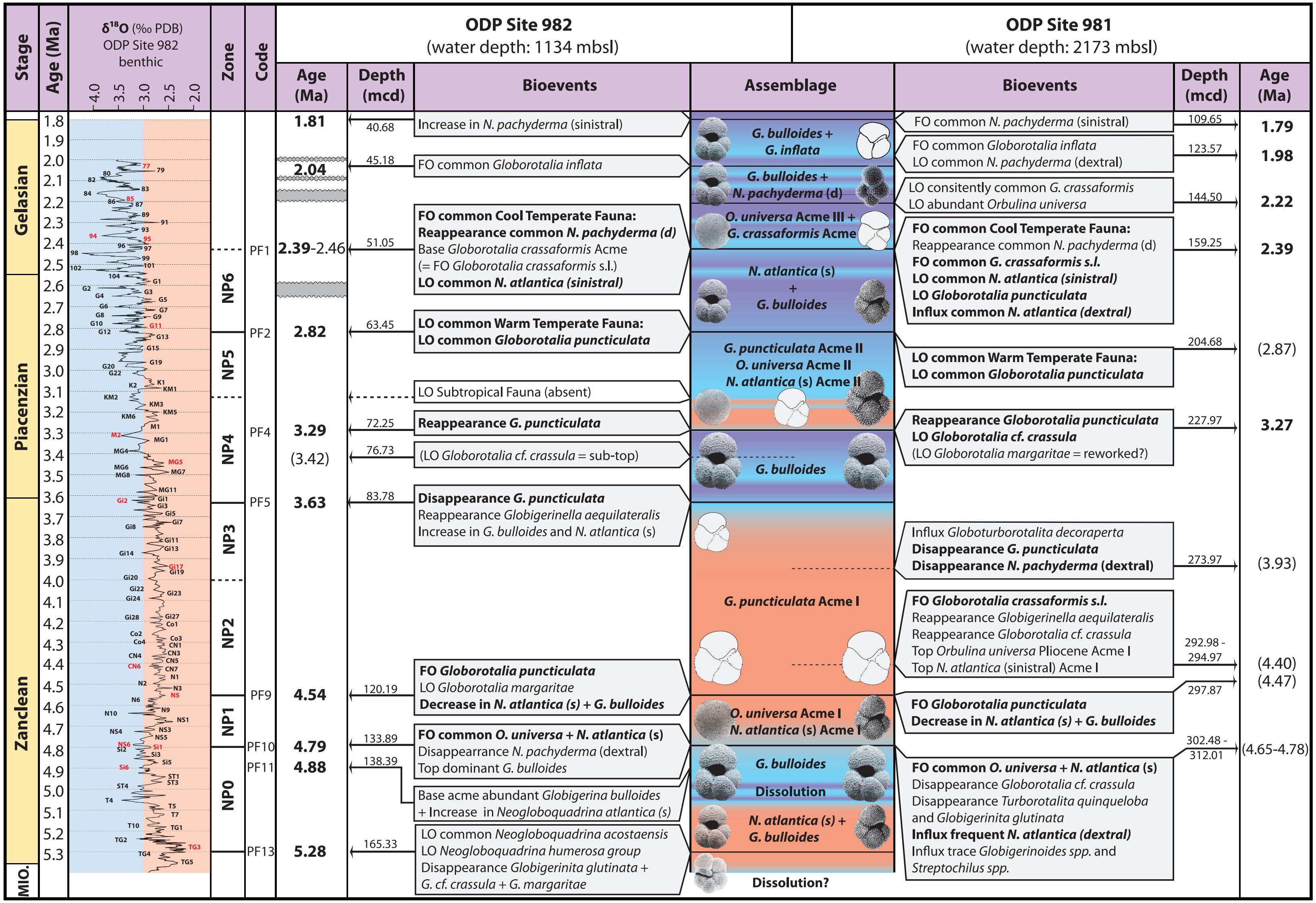


Fig. 3. Pliocene planktonic foraminiferal acme events on the Rockhall Plateau. The basis for the interpretation of species acme intervals and events are the raw fossil counts from ODP Leg 162, in Flower (1999). ODP Site 982 ages are calibrated to the high-resolution astronomically tuned oxygen isotope stratigraphy of Hodell et al. (2001). ODP Site 981 ages are calibrated to the magnetostratigraphy of Channell and Lehman (1999) and the oxygen isotope record of Draut et al. (2003) (3.2–3.3 Ma). Ages in parenthesis are based on their original Site 981 age model, but using updated magnetochron ages in Lourens et al. (2004). Grey shaded time intervals are periods of low sedimentation rate and possible hiatuses. The oxygen isotope record for Site 982 is a composite of the following studies: 5.3–4.6 Ma = Hodell et al. (2001); 4.6–3.6 Ma = Lisiecki and Raymo (2005); 3.6–2.0 Ma = Mudelsee and Raymo (2007). Oxygen isotope stage durations are according to Lisiecki and Raymo (2005). Isotope stages in red coincide with the respective bioevents. The warm to cold (red to purple) paleotemperature interpretation is based on a combination of the oxygen isotope curve and the inferred (paleo)ecological preferences of the assemblage succession.

vidual bioevent age calibrations have been expressed as ranges. Where a bioevent age is given to one decimal place only, the intention is to account for either very low sample resolution, large age/depth uncertainties of bracketing intervals, or the often numerous occurrences of barren bracketing intervals.
The resulting bioevent ages, their calibration points and sites are summarised in Table 2. For details of individual event calibrations and depths by site, see Appendix 1.

3.2 Materials and Methods: Nordic high-latitude local correlations (North Sea)

So as to better constrain the mainly benthic foraminiferal based biostratigraphy of the North Sea, outcrop samples from the Ramsholt Member of the Coralline Crag Formation (East Anglia, UK) together with selected North Sea industrial well intervals were analysed for their foraminiferal components (Table 1). The cored intervals analysed from the northern North Sea represent a higher quality of study material than previously available here. The choice of these cores was based on the assumption that better sample recovery would reveal more diverse assemblages and a higher degree of stratigraphic precision than what normally would be available from analysis of ditch cutting material.

While sample preparation for Well 29/3–1 and Well 16/1–1 was not conducted by the author, the size fraction analyzed suggests standard micropaleontological preparation techniques were used, with a mesh size of 63 microns. All other well and outcrop samples were prepared by the author using standard procedures involving boiling of samples in a solution of water and sodium hexa-metaphosphate, wet sieving through a 63 micron mesh, followed by oven drying.

Microscope analysis involved identification and counting, where possible, of approximately 300 benthic and planktonic foraminiferal individuals per sample. The main micropaleontological results are shown in Figure 4 together with published palynological findings from the same sections according to Piasecki et al. (2002) and Head (1997). For detailed quantitative foraminiferal and bolboformid counts see Appendix 2.

4.1 Results: A new Nordic Pliocene Zonation

Based on the results of the age-calibrations presented in Table 2 and Appendix 1, the following multi-group microfossil zonation currently represents the most refined and well-constrained biostratigraphic framework for the Lower to mid-Pliocene of the Nordic Atlantic region.

The Nordic Pliocene (NP) Zones presented here are essentially all assemblage zones (Fig. 2). Last occurrence events have been favoured over first occurrences. This facilitates application to industrial wellbore samples, where downhole contamination may be prevalent. Unlike traditional single-group zonations, this multi-group combination of a total of 51 bioevents

Table 1 North sea well and outcrop samples analysed for foraminifreal content in this study. Lithostratigraphy for the North sea wells follows Eidvin and Rundberg (2007) and the updated Norwegian Lexicon (NORLEX), available at http://norges.uio.no.

Well/Outcrop	Coordinates	Lithostratigraphic unit	Depth interval (m MD)	Sample type
34/8-A-1H	61° 22′ 12.57″ N 2° 27′ 35.13″ E	Utsira Member (Kai Formation)	1069.00–1103.67	conventional cores
29/3-1	60° 57′ 50.24″ N 1° 56′ 13.25″ E	Lark Formation	683–1381	ditch cuttings
16/1-1	58° 59′ 17.65″ N 2° 02′ 03.00″ E	Utsira Member (Kai Formation)	689.00–752.87	conventional cores/ core chips
15/9-A-23	58° 22′ 02.05″ N 1° 54′ 32.06″ E	Utsira Member (Kai Formation)	1079.45–1088.35	conventional cores
Rockhall Wood, Ramsholt, East Anglia (UK)	52° 02′ 47.02″ N 1° 21′ 32.28″ E	Ramsholt Member (Coralline Crag Formation)	6.4–0.5 m above base Ramsholt Member	outcrop

(28 foraminifers and bolboforms; 17 dinoflagellate cysts and acritarchs; 6 marine diatoms) facilitates zonal identification throughout the Nordic Atlantic region by both micropaleontologists and palynologists alike. For many of the planktonic foraminiferal events, identification of additional quantitative assemblage changes and acme/paracme intervals facilitates bioevent identification (Fig. 3). This additional parameter for event identification is especially useful north of the Greenland-Scotland Ridge (e.g. northern North Sea and offshore Mid-Norway), where much lower diversity planktonic foraminiferal assemblages occur (Eidvin et al. 2000, Spiegler and Jansen 1989).

The definition of zonal boundaries as coinciding with multiple marker events results in the ages of four boundaries in particular appearing to be stratigraphically uncertain. However, this deliberate boundary interval of only 100,000 years duration allows for a much greater range of zonal markers, thus significantly increasing usability. While these boundary intervals might pose a problem in defining zonal boundaries in extremely high-resolution integrated data-sets, they significantly increase the utility of this zonation in the more readily available petroleum industry sections. In addition, the bioevents marking these boundary intervals often appear to belong to the same faunal province and occur in similar biofacies (i.e. subtropical, warm temperate and cool temperate faunas and floras). They have been grouped into 'boundary event clusters' according to their most reliable age-calibrations (Table 2). Zonal duration ranges from 300,000 to 600,000 years. Ages of zonal boundaries follow that of the 'boundary event clusters' in Table 2. First time occurrences (uphole) are abbreviated to "FO" and last time occurrences (uphole) to "LO", following common petroleum industry practice.

Nordic Pliocene Zone NP0

Age: 5.3/5.2–4.8 Ma

Lower boundary (5.3–5.2 Ma): This level is marked by marine diatom event MD5 (FO *Thalassiosira oestrupii* and/or LO *Thalassiosira nativa*). Additional markers are the planktonic foraminiferal events PF12 (LO *Neogloboquadrina continuosa*) and PF13 (LO common *Neogloboquadrina acostaensis* and/or (LO *N. humerosa group*).

Upper boundary (4.8 Ma): This level is marked by the planktonic foraminiferal event PF10 (Top of dominant *Globigerina bulloides*; base of Pliocene Acme 1 of *Orbulina universa* and *Neogloboquadrina atlantica* (sinistral coiling); disappearance of *Neogloboquadrina pachyderma* (dextral coiling); influx of frequent *Neogloboquadrina atlantica* (dextral coiling)) and by the dinoflagellate cyst event DC17 (FO Cyst type 1 of de Vernal and Mudie 1989).

Intrazonal events: The planktonic foraminiferal event PF11 (base of *Globigerina bulloides* acme and an increase in *Neogloboquadrina atlantica* [sinistral coiled]) occurs within this zone.

Nordic Pliocene Zone NP1

Age: 4.8–4.5 Ma

Lower boundary (4.8 Ma): Equivalent to the top of Zone NP0.

Upper boundary (4.5 Ma): This level is marked by the dinoflagellate cyst/acritarch events DC13 (FO *Leiosphaeridia rockhallensis*), DC14 (Influx *Tectatodinium pellitum*) and DC15 (LO *Reticulatosphaera actinocoronata*). Planktonic foraminiferal marker events are PF8 (FO *Globorotalia crassaformis* group) and PF9 (FO *Globorotalia puncticulata*). In the North Sea and offshore Mid-Norway the benthic foraminiferal event BF4 (LO common *Nonion boueanum* and/or common *Uvigerina venusta* group) occurs at this level.

Intrazonal events: The marine diatom event MD5 (LO *Thalassiosira jacksonii*) and the dinoflagellate cyst event DC16 (FO *Corrudinium devernaliae*) occur within this zone.

Nordic Pliocene Zone NP2

Age: 4.5–4.3/4.2 Ma

Lower boundary (4.5 Ma): Equivalent to the top of the preceding zone.

Upper boundary (4.3–4.2 Ma): This level is marked by the dinoflagellate cyst events DC12 (FO *Filisphaera filifera*), DC11 (LO common *Amiculosphaera umbracula*) and DC10 (LO Cyst type 1 of de Vernal and Mudie 1989). The bolboformid event BO3 (FO *Bolboforma costairregularis costairregularis*) also marks this level. The rare planktonic foraminiferal event PF7 (FO *Globorotalia crassaformis viola*), only recorded south of the Greenland-Scotland Ridge (See Fig. 1), is a secondary marker for the high-latitude North Atlantic.

Intrazonal events: The marine diatom event MD4 (LO *Stephanogonia hanzawae;* FO *Thalassiosira nidulus*) and the bolboformid event BO4 (LO *Bolboforma costairregularis variabilis*) occur within this zone.

Nordic Pliocene Zone NP3

Age: 4.3/4.2–3.6 Ma

Lower boundary (4.3–4.2 Ma): Equivalent to the top of the preceding zone.

Upper boundary (3.6 Ma): This level is marked by the planktonic foraminiferal event PF5 (Disappearance of *Globorotalia puncticulata;* (Second) Disappearance of *Neogloboquadrina pachyderma* (dextral coiled); Reappearance *Globigerinella aequilateralis*; Base of a *Globigerina bulloides* dominated assemblage). Dinoflagellate cyst events marking this level are DC7 (LO (consistent) *Batiacasphaera minuta*), DC6 (LO *Melitasphaeridium choanophorum*) and DC5 (LO *Operculodinium tegillatum*).The bolboformid event BO2 (FO *Bolboforma elegans*) is a secondary marker. The benthic foraminiferal event BF3 (LO (consistent) *Uvigerina venusta* group; LO *Pullenia bulloides*; LO *Sphaeroidina bulloides*; LO *Cibicides dutemplei* group and LO *Globocassidulina subglobosa*) occurs at this level in the North Sea and offshore Mid-Norway. In the offshore of Mid-Norway the marine diatom/siliceous event MD3 (LO common diatoms, radiolaria and sponge spicules, including *Geodia spp*.) is an additional marker.

Intrazonal events: The dinoflagellate cyst/acritarch events occurring within this zone are DC9 (LO *Corrudinium devernaliae*) and DC8 (LO *Leiosphaeridia rockhallensis*).The planktonic foraminiferal event PF6 (LO *Globorotalia margaritae*) has only been recorded south of the Greenland-Scotland Ridge. Its last occurrence appears to be highly diachronous from mid- to high latitudes in the North Atlantic and is therefore only tentatively placed in this zone.

Nordic Pliocene Zone NP4

Age: 3.6–3.2/3.1 Ma

Lower boundary (3.6 Ma): Equivalent to the top of the preceding zone.

Upper boundary (3.2–3.1 Ma): This level is marked by the planktonic foraminiferal events PF3a (LO *Dentoglobigerina altispira*), PF3b (LO *Sphaeroidinellopsis seminulina* s.l.) and PF3c (LO (consistent) *Neogloboquadrina atlantica* (sinistral coiled) – offshore Mid-Norway only). In the North Sea and offshore Mid-Norway the benthic foraminiferal event BF2 (FO *Elphidiella hannai*; Top acme *Bulimina aculeata/marginata* group; LO common *Textularia decrescens*, LO common *Spiroplectammina sagittula* group and LO common *Sigmoilopsis schlumbergeri*; LO *Cibicides limbatosuturalis* – tentative) is an additional marker for this level.

Intrazonal events: Occurring within this zone are the planktonic foraminiferal event PF4 (Reappearance of *Globorotalia puncticulata*; LO *Globorotalia cf. crassula*; Top of a *Globigerina bulloides* dominated assemblage) and the marine diatom event MD2 (LO *Thalassiothrix miocenica*; LO *Proboscia barboi*).

Nordic Pliocene Zone NP5

Age: 3.2/3.1–2.8/2.7 Ma
Lower boundary (3.2–3.1 Ma): Equivalent to the top of the preceding zone.

Upper boundary (2.8–2.7 Ma): This level is marked by the planktonic foraminiferal event PF2 (LO common *Globorotalia puncticulata*).Dinoflagellate cyst markers are DC4 (LO *Barssidinium* spp.), DC3 (LO common *Invertocysta lacrymosa*) and DC2 (LO *Selenopemphix brevispinosa*). Additional markers include the calcareous nannofossil events CN2 (LO *Discoaster tamalis*) and CN1 (LO *Discoaster surculus*).

Intrazonal events: Occurring within this zone are the marine diatom event MD1 (LO *Nitzschia jouseae*) and the bolboformid event BO1 (LO *Bolboforma costairregularis costairregularis; LO Bolboforma* genus).

Nordic Pliocene Zone NP6

Age: 2.8/2.7–2.5 Ma

Lower boundary (2.8–2.7 Ma): Equivalent to the top of the preceding zone.

Upper boundary (2.5 Ma): This level is marked by the dinoflagellate cyst event DC1 (Base of the first uphole acme of *Filisphaera filifera*) and the benthic foraminiferal event BF1 (LO *Monspeliensina pseudotepida*).The latter event may occur slightly older at upper neritic to bathyal paleodepths.

Intrazonal events: The planktonic foraminiferal event PF1 (LO common *Neogloboquadrina atlantica* [sinistral coiled]) occurs within this zone.

Table 2 Summary of Nordic Pliocene Zones (NPZ) and bioevent calibrations for the Nordic Atlantic region. Bioevent ages are organised from south to north according to latitudinal region. Ages are according to the calibrations in this study, except for those according to the Astronomically Tuned Neogene Time Scale (ATNTS04) of Lourens

Age of boundary event cluster (MA)	**Nordic Pliocene Zone**	**Bioevent code** (* = rare event in Nordic region)	**Age by region** (Ma)				
			Time scale ATNTS04 M = E. Medit.; A = S. Atlantic	35°–50° N Mid – High North Atlantic	50°–63° N High North Atlantic	63°–70° N Nordic Seas & North Sea	70°–80° N Arctic
2.5	top NP6	DC1				**2.5–2.6**	~ 2.4
		BF1				**2.5**	
2.5	**NP6**	PF1			**2.39**	**2.6**	
2.7–2.8	NP5/NP6	CN1*	2.54 (M)	2.54–2.59	**2.72**–2.75		
2.7–2.8	NP5/NP6	DC2				(2.7) > 2.6	~ 2.6
2.7–2.8	NP5/NP6	DC3		2.74	2.74–2.78	> 2.74	(> 2.56)
2.7–2.8	NP5/NP6	DC4	2.55 (M) in Versteegh (1995, 1997)		**2.74**	**2.7**–3.3	

et al. 2004. Bioevent codes: CN = Calcareous Nannofossil; PF = Planktonic Foraminifera; BF = Benthic Foraminifera; BO = Bolboforma; DC = Dinoflagellate cyst or acritarch. For details of individual age calibrations and references see Appendix.

Bioevent(s)	**Calibration(s)** (magnetosubchron/ isotope stage/ nanofossil zone	**Calibration site(s)** (IODP/ODP/DSDP, industrial wells outcrops)	**References** + Lourens et al. (2004)
Base of the first uphole acme of Filisphaera filifera (= Base lower/last downhole acme of F. filifera, in Anthonissen 2008)	Near top C2An. 1n′; Within C2r.2r″	Cored Wells B10–3, B13–3 and B17–5/B17–6′; 642′; 911″	Kuhlmann (2004); Anthonissen (2008)
LO Monspeliensina pseudotepida; Base acme Bulimina aculeata/marginata group	Above top C2An.1n′, Interval with a 87Sr/86Sr isotope ratio of 0.709,047–0.709,051 (= 2.5–4.5 Ma)″	Cored Wells A15–3 and B10–3′; Partial Cored Well 2/4-C-11″	Kuhlmann (2004); Eidvin et al. (1999); Anthonissen (2008)
(i) LO consistently common Neogloboquadrina atlantica (sinistral); (ii) Influx N. atlantica (dextral); Reappearrance common N. pachyderma (d); LO Globorotalia puncticulata	(i) Top C2An.1n; (ii) MIS 95–97	(i) Cored Wells A15–3 and B10–3, (ii) 981A, 982B	Kuhlmann (2004); Flower (1999); Anthonissen (2008
LO Discoaster surculus	C2r.2r/C2An.1n′ to C2An.1n″, MIS G6-G6/G7″′	400A′, 603C′, 981A″, 982B″′, 646B	Mueller (1979); Muza et al. (1987); Shipboard Scientific Party (1996a); Knuttel and Firth (1989); Anthonissen (2008)
LO Selenopemphix brevispinosa	? lower C2r.2r′	986D′, Kattendijk Formation	Channell et al. (1999b); Louwye et al. (2004)
LO common Invertocysta lacrymosa	MIS G6 (100)-MIS G7 (111)′, mid C2An.1n″, NN16″′	Singa Section′, 610A′, 607′′, 400A′′, 646B′″, Lillo Formation, Coralline Crag Formation, 986D	Versteegh (1997); De Schepper and Head (2008); Mudie (1986); Mueller (1979); de Vernal and Mudie (1989); Head (1997); Louwye et al. (2004); Channell et al. (1999b)
LO Barssidinium spp. (including B. pliocenicum)	MIS G7 (111)′, C2An.2r/ C2An.3n″, Reuverian B Pollen Substage″′	Cored Wells A15–3 and B10–3′′, Red Crag Formation′″, Coralline Crag Formation	De Schepper and Head (2008); Kuhlmann (2004); Head (1998); Head (1997)

Table 2 continued.

Age of boundary event cluster (MA)	**Nordic Pliocene Zone**	**Bioevent code** (* = rare event in Nordic region)	**Age by region** (Ma)				
			Time scale ATNTS04	35°–50° N	50°–63° N	63°–70° N	70°–80° N
			M = E. Medit,; A = S. Atlantic	Mid – High North Atlantic	High North Atlantic	Nordic Seas & North Sea	Arctic
2.7–2.8	NP5/NP6	CN2*	2.80 (M); 2.80 (A)		**2.80**–3.00		
2.7–2.8	NP5/NP6	PF2			**2.82**–2.87		
	NP5	MD1		**2.84**–2.89	**2.87**–2.89		
		BO1			**2.93**(3.39)		
3.1–3.2	NP5/NP5	PF3a*	3.13 (A); 3.17 (M)	**3.1**–3.2			(> 3.63)
3.1–3.2	NP5/NP5	PF3b*	3.13 (A); 3.19 (M)	**3.13**–3.21	(5.35)		(> 3.6)
3.1–3.2	NP5/NP5	PF3c				**3.11**	
3.1–3.2	NP5/NP5	BF2				**3.2** (3.0–3.3)	

Bioevent(s)	Calibration(s) (magnetosubchron/ isotope stage/ nanofossil zone	Calibration site(s) (IODP/ODP/DSDP, industrial wells outcrops)	References + Lourens et al. (2004)
LO Discoaster tamalis	C2An.1n′; (MIS G9)	981A′, 646B′, (982B), (552A)	Lourens et al. (2004); Shipboard Scientific Party (1996a); Knuttel and Firth (1989); Backman (1984)
LO common Globorotalia puncticulata (Top G. puncticulata Acme II)	MIS G11′	982B′, 981A	Flower (1999); Hodell et al. (2001), Lisiecki and Raymo (2005), Draut et al. (2003) + This study
LO Nitzschia jouseae	C2An.1n, MIS G15	606, 610A, 552A	Baldauf (1987); Baldauf (1984); Keigwin (1984) + This study
LO Bolboforma costairregularis costairregularis; LO Bolboforma genus	MIS G16/G17′, C2An.1n′; (MIS MG5′′)	982B′, (552A″)	Spiegler (1999) + Hoddell et al. (2001) + This study; Murray (1986)
LO Dentoglobigerina altispira	C2An.1r (Kaena)	606, 607, 607A, 910D	Lourens et al. (2004); Weaver and Clement (1986); Spiegler (1996)
LO Sphaeroidinellopsis seminulina s. l.	C2An.2n	606, 607, (607A), (918D), (910D)	Lourens et al. (2004); Weaver and Clement (1986); Spezzaferri (1998); Spiegler (1996)
LO (consistent) Neogloboquadrina atlantica (s) (Offshore Mid-Norway only)	? C2An.1r′	642B′, 643A′, Mid-Norway well blocks 6406, 6407, 6507, 6508 and 6609	Spiegler and Jansen (1989); Bleil (1989); Eidvin et al. (2007)
(i) FO Elphidiella hannai; (ii) Top acme Bulimina aculeata/ marginata group +/- Melonis ex gr. barleeanus; (iii) LO common Pliocene agglutinates: LO common Textularia decrescens, Spiroplectammina sagittula, Sigmoilopsis schlumbergeri;?LO Cibicides limbatosuturalis	(i&ii) C2An.1n/C2An.1r – C2An.2r/C2An.3n; (iii) Coincident with PF3	(i&ii) Cored Wells A15–3 and B10–3; (iii) Central North Sea Wells 2/4-C-11 and 15/12–3 and Mid-Norway well blocks 6406, 6407, 6507, 6508 and 6609	Kuhlmann (2004); Eidvin et al. (1999); Eidvin et al. (2007)

Table 2 continued.

Age of boundary event cluster (MA)	**Nordic Pliocene Zone**	**Bioevent code** (* = rare event in Nordic region)	**Age by region** (Ma)				
			Time scale ATNTS04 M = E. Medit,; A = S. Atlantic	35°–50° N Mid – High North Atlantic	50°–63° N High North Atlantic	63°–70° N Nordic Seas & North Sea	70°–80° N Arctic
	NP4	PF4		(i) 3.31; (ii) 3.12–3.15	**(i)** **3.27**–3.29; (ii) 3.16–**3.27**		
	NP4	MD2				**3.33**–3.35	
3.6	NP3/NP4	DC5			3.57–3.90 (4.2)	< 4.3	
3.6	NP3/NP4	DC6		**3.6**–3.8		**3.6**–3.8 (4.2)	(5.0–5.2)
3.6	NP3/NP4	DC7		(3.33) **3.60**	3.83–3.88	3.6–4.31	
3.6	NP3/NP4	BO2			3.53–**3.63**		
3.6	NP3/NP4	PF5		3.57	**3.63** (3.93)		
3.6	NP3/NP4	BF3				3.6	

Bioevent(s)	Calibration(s) (magnetosubchron/ isotope stage/ nanofossil zone	Calibration site(s) (IODP/ODP/DSDP, industrial wells outcrops)	References + Lourens et al. (2004)
(i) Reappearance G. puncticulata (Base Globorotalia puncticulata Acme II); (ii) LO G. cf. crassula; (iii) Top Globigerina bulloides dominated assemblage	(i) MIS M2; (ii) C2An.2n – C2An.2r, (MIS KM3-KM6′′); (iii) MIS M2	(i) U1312, U1313, 982B, 981A; (ii) 606, 607, 609, (609B), (610A), 611C, 981A, (982B′′); (iii) 982B, 981A	Expedition Scientists (2005); Flower (1999) + This study; Weaver and Clement (1986) + This study
LO Thalassiothrix miocenica; LO Proboscia barboi	C2An.3n	907A	Koc and Scherer (1996)
LO Operculodinium tegillatum	NN15′,?C2An.3n″, C2Ar‴′	646B′, 611C″, 610A‴′, Coralline Crag Formation, Kattendijk Formation	de Vernal and Mudie (1989); Mudie (1987); De Schepper and Head (2008); Head (1997); Louwye et al. (2004)
LO Melitasphaeridium choanophorum	near C2An.3n/C2Ar′- C2Ar″	400A, Cored Wells A15-3 and B10-3′, 646B′′, 642C′′, (642B), Coralline Crag Formation, (909C)	Harland (1979); Kuhlmann (2004); de Vernal And Mudie (1989); Mudie (1989); Head (1987); Poulsen et al. (1996)
LO (consistent) Batiacasphaera minuta (= B. micropapillata, B. sphaerica, Tectatodinium minutum)	C2An.3n′, NN15″, C2Ar‴′, (C3r′‴′)	603C′, 646B″, 610A‴′,(642B′‴′) Coralline Crag Formation	De Schepper and Head (2008); de Vernal and Mudie (1989); Louwye et al. (2004); Head (1997)
FO Bolboforma elegans	MIS MG9 – MIS Gi2	982B	Spiegler (1999) + Hoddell et al. (2001) + This study
Disappearance G. puncticulata (Top Globorotalia puncticulata Acme I); Reappearance of Globigerinella aequilateralis; Disappearance of Neogloboquadrina pachyderma (dextral); Base Globigerina bulloides dominated assemblage	MIS Gi2′	U1312, U1313, 982B′, (981A)	Expedition Scientists (2005); Flower (1999) + This study
LO (consistent) Uvigerina venusta group, Pullenia bulloides, Sphaeroidina bulloides, Cibicides dutemplei group and Globocassidulina subglobosa	Coincident with PF5	Central North Sea Well 2/4-C-11, Offshore Mid-Norway Wells 6508/5-1 and 6407/9-5	Eidvin et al. (1999) + This study; Eidvin et al. (2007) + This study

Table 2 continued.

Age of boundary event cluster (MA)	**Nordic Pliocene Zone**	**Bioevent code** (* = rare event in Nordic region)	**Age by region** (Ma)				
			Time scale ATNTS04 M = E. Medit,; A = S. Atlantic	35°–50° N Mid – High North Atlantic	50°–63° N High North Atlantic	63°–70° N Nordic Seas & North Sea	70°–80° N Arctic
3.6	NP3/NP4	MD3				3.6	
	NP3	DC8		3.81–3.87	**3.83**	3.6–4.3	
	NP3	PF6*	3.81 (M); 3.85 (A)	**3.98**–3.99	**4.51**–4.56		
	NP3	DC9		**4.02**–4.11	(3.90) 3.95–3.97		
4.2–4.3	NP2/NP3	PF7*			3.76–**4.15**		
4.2–4.3	NP2/NP3	DC10		**4.19**–4.30	4.09–4.11		
4.2–4.3	NP2/NP3	DC11				**4.21**–4.22 (5.03)	
4.2–4.3	NP2/NP3	DC12			**4.24** (5.7)	4.24–4.52 (5.1)	
4.2–4.3	NP2/NP3	BO3			**4.31**		
	NP2	MD4				**4.35**–4.52	

Bioevent(s)	Calibration(s)	Calibration site(s)	References + Lourens et al. (2004)
	(magnetosubchron/ isotope stage/ nanofossil zone	(IODP/ODP/DSDP, industrial wells outcrops)	
LO common diatoms, radiolaria and sponge spicules including Geodia spp. (Offshore Mid-Norway only)	Coincident with PF5	Offshore Mid-Norway Wells 6508/5-1 and 6407/9-5	Eidvin et al. (2007) + This study
LO Leiosphaeridia rockhallensis	C2Ar′	603C′, 610A′, Coralline Crag Formation	Head and Norris (2003); De Schepper and Head (2008); Head (1997)
LO Globorotalia margaritae	C2Ar′, MIS N5″	(606), 607′,(981A), 982B′′, 116, 609, (609A), (610A), (611C)	Weaver and Clement (1986); Flower (1999) + Hoddell et al. (2001) + This study; Poore and Berggren (1975)
LO Corrudinium devernaliae	C2Ar′, mid-NN15″	603C′, 646B′′, (610A)′	Head and Norris (2003) + De Schepper and Head (2008); de Vernal and Mudie (1989); Knuttel and Firth (1989)
FO Globorotalia crassaformis viola	C2Ar	609, 611C	Bylinskaya (2005)
LO Cyst type I of de Vernal & Mudie (1989)	C3n.1n′, NN14″	603C′, 646B′′	Head and Norris (2003); de Vernal and Mudie (1989); Knuttel and Firth (1989)
LO common Amiculosphaera umbracula	C3n.1n′	642B′, (642C)	Mudie (1989) + This study; Bleil (1989)
FO Filisphaera filifera	C3n.1n′	(607), 611C′, 642B′, 642C, (643A), (987E), (646B)	Mudie (1987); Mudie (1989); Channell et al. (1999b); de Vernal and Mudie (1989
FO Bolboforma costairregularis costairregularis	MIS CN1	82B	Spiegler (1999) + Hoddell et al. (2001) + This study
LO Stephanogonia hanzawae; FO Thalassiosira nidulus	C3n.1r	907A	Koc and Scherer (1996)

Table 2 continued.

Age of boundary event cluster (MA)	**Nordic Pliocene Zone**	**Bioevent code** (* = rare event in Nordic region)	**Age by region** (Ma)				
			Time scale ATNTS04	35°–50° N	50°–63° N	63°–70° N	70°–80° N
			M = E. Medit,; A = S. Atlantic	Mid – High North Atlantic	High North Atlantic	Nordic Seas & North Sea	Arctic
	NP2	BO4			**4.36**	4.73–4.78	
4.5	NP1/NP2	DC13		4.43–**4.46**			
4.5	NP1/NP2	DC14				4.44–**4.52** (5.33)	
4.5	NP1/NP2	DC15		4.63–4.80	**4.53**–4.71	4.51–4.65	(5.0–5.2)
4.5	NP1/NP2	PF8a*			3.96–**4.53**		
4.5	NP1/NP2	PF8b*			4.23–**4.53**		
4.5	NP1/NP2	PF8c	4.31 (A)	(4.44) 4.51–4.55 (4.61)	(4.44) 4.51–**4.53**(4.61)		
4.5	NP1/NP2	PF9	4.52 (M)	(4.44) 4.51–4.55 (4.61)	(4.47) 4.52–**4.54** (4.56)		
4.5	NP1/NP2	BF4				4.54	

Bioevent(s)	**Calibration(s)** (magnetosubchron/ isotope stage/ nanofossil zone	**Calibration site(s)** (IODP/ODP/DSDP, industrial wells outcrops)	**References** + Lourens et al. (2004)
LO Bolboforma costairregularis variabilis	MIS CN4′,?mid-NN15″, C3n.2r‴	982B′, 116″, 642B‴, 642C	Spiegler (1999) + Hoddell et al. (2001) + This study; Qvale and Spiegler (1989) + Bleil (1989)
FO Leiosphaeridia rockhallensis	C3n.1r	603C	Head and Norris (2003) + Lourens et al. (2004)
Influx Tectatodinium pellitum	C3n.1n′	642B′, (643A)	Mudie (1989) + Bleil (1989) + This study
LO Reticulatosphaera actinocoronata	C3n.2r′, C3n.4n″, C3n.2n-C3n.2r‴, C3n.2n⁗	603C′, 607″, 611C‴, (642B), 642C, (643A), (907A), (909C), 987E⁗, cored well 15/9-A-23, Kattendijk Formation	Head and Norris (2003); Mudie (1987); Mudie (1989); Poulsen et al. (1996); Channell et al. (1999b); Piasecki et al. (2002); Louwye et al. (2004)
FO Globorotalia crassaformis hessi	C2Ar′, C3n.2n″	611C′, 609′′	Bylinskaya (2005)
FO Globorotalia crassaformis ronda	C3n.1n′, C3n.2n″	611C′, 609′′	Bylinskaya (2005)
FO Globorotalia crassaformis crassaformis (s. l.)	(C3n.1r)-C3n.2n′, C3n.2n″	607′, 606A′′, (609′′), 611C′′, (981A)	Lourens et al. (2004); Weaver and Clement (1986); Bylinskaya (2005); Flower (1999)
FO Globorotalia puncticulata (Base G. puncticulata Acme I); Decrease in Neogloboquadrina atlantica (s) + Globigerina bulloides	(C3n.1r)-C3n.2n′, C3n.2n″, MIS N5‴	607′, 606A″, (609″), (981A), 982B‴	Weaver and Clement (1986) + Lourens et al. (2004); Flower (1999) + Hoddell et al. (2001) + This study
LO common Nonion boueanum and/or common Uvigerina venusta group	Coincident with PF9′; Coincident with DC15″	Central North Sea Well 2/4-C-11′, Offshore Mid-Norway Wells 6508/5–1′ and 6407/9–5″; Top Kattendijk Formation″; Breda Formation″	Eidvin et al. (1999) + This study; Eidvin et al. (2007) + This study; Louwye et al. (2004); Doppert et al. (1979)

Table 2 continued.

Age of boundary event cluster (MA)	**Nordic Pliocene Zone**	**Bioevent code** (* = rare event in Nordic region)	**Age by region** (Ma)				
			Time scale ATNTS04	35°–50° N	50°–63° N	63°–70° N	70°–80° N
			M = E. Medit,; A = S. Atlantic	Mid – High North Atlantic	High North Atlantic	Nordic Seas & North Sea	Arctic
	NP1	MD5				**4.71**–4.90	
	NP1	DC16		**4.73**(4.86)			
4.8	NP0/NP1	PF10			4.78–**4.79**		
4.8	NP0/NP1	DC17		4.63–**4.80**	4.89 (5.08)		
	NP0	PF11			**4.88**	4.96–5.02	
	NP0	PF12		**5.2**	5.14–5.18	5.59–5.66	
5.2–5.3	base NP0	MD6			5.02–**5.27**	5.03–5.09	
5.2–5.3	base NP0	PF13			**5.28**	6.23–6.24 (6.35)	
5.2–5.3	base NP0	BO5			(4.95) **5.76**	(4.86) 5.60–5.65	

Bioevent(s)	**Calibration(s)**	**Calibration site(s)**	**References** + Lourens et al. (2004)
	(magnetosubchron/ isotope stage/ nanofossil zone	(IODP/ODP/DSDP, industrial wells outcrops)	
LO Thalassiosira jacksonii	C3n.2r	907A	Koc and Scherer (1996) + Lourens et al. (2004)
FO Corrudinium devernaliae	C3n.2r′, C3n.3n″	603C′, 607/607A′′	Head and Norris (2003) + Lourens et al. 2004, De Schepper and Head (2008)
Top dominant Globigerina bulloides; Base Pliocene Acme I of Orbulina universa + Neogloboquadrina atlantica (s); Disappearrance of N. pachyderma (dextral); Influx frequent N. atlantica (d)	MIS NS6-Si1	981A, 982B	Flower (1999 + Hoddell et al. (2001) + This study
FO Cyst type I of de Vernal & Mudie (1989)	C3n.2r′, NN12″	603C′, 646B′′	Head and Norris (2003) + Lourens et al. (2004); de Vernal and Mudie (1989) + Knuttel and Firth (1989)
Base acme abundant Globigerina bulloides and increase in Neogloboquadrina atlantica (s)	MIS Si6′, C3r.3r″	982B′, 642B′′, 642C′′	Flower (1999 + Hoddell et al. (2001) + This study; Spiegler and Jansen (1989) + Bleil (1989)
LO Neogloboquadrina continuosa (= N. atlantica praeatlantica)	C3n.4n′, C3r″	607′, 611C′, 642B″	Weaver and Clement (1986) + This study; Spiegler and Jansen (1989) + Bleil (1989)
FO Thalassiosira oestrupii and/or LO Thalassiosira nativa	NN12/13′, C3n.4n″	552A′, 642C″	Boden (1992)
LO common/consistent Neogloboquadrina acostaensis and/or LO N. humerosa group	MIS TG3′, C3An.1n″, (C3An.1r″′)	982B′, 642C″, (642B″′)	Flower (1999 + Hoddell et al. (2001) + This study; Spiegler and Jansen (1989) + Bleil (1989)
FO Bolboforma costairregularis variabilis	(NN12/12′), C3r″, (C3n.3n″)	982B, (116′), 642C″, (642B′″)	Spiegler (1999) + Hoddell et al. (2001) + This study; Qvale and Spiegler (1989) + Bleil (1989)

4.2 Results: Identification of the Zanclean and Piacenzian Stages

Base Piacenzian Stage (3.600 Ma)

The base of the Piacenzian can be identified outside of the Mediterranean type area (as applicable to this study) by the following correlative events according to Castradori et al. (1998): 1) the Gauss-Gilbert (C2An.3n-C2Ar) magnetic reversal (3.596 Ma in Lourens et al. 2004); 2) Marine Oxygen Isotope Stage 176 (= Gi1 in Lisiecki and Raymo 2005); the calcareous nannofossil last occurrence (LO) of *Sphenolithus* spp. (3.54–3.70 Ma in Lourens et al. 2004); and the planktonic foraminiferal LO *Globorotalia margaritae* (3.81–3.85 Ma in Lourens et al. 2004). Both fossil events are rare occurrences in the high-latitude North Atlantic, and completely absent from sites north of the Greenland-Scotland Ridge. The last occurrence of *G. margaritae*, PF6 in this study, appears to be strongly diachronous across the region. In the mid- to high-latitude central North Atlantic it disappears at 3.98 Ma, while in the high-latitude North Atlantic (Rockall Plateau) it disappears at 4.51 Ma, coincident with the first occurrence of the warm temperate fauna.

The base of the Piacenzian Stage is more easily identified in the Nordic region by the NP3/NP4 zonal boundary at approximately 3.6 Ma.

Base Zanclean Stage, base Pliocene Series (5.332 Ma)

The base of the Zanclean can be identified outside of the Mediterranean type area (as applicable to this study) by the following correlative events according to Van Couvering et al. (2000): 1) near the base of the Thvera (C3n.4n) normal subchron (5.235 Ma in Lourens et al. 2004), within the lowermost reversed episode of the Gilbert Chron (C3r); 2) the calcareous nannofossil first occurrence (FO) of *Ceratolithus acutus* (5.35 Ma in Lourens et al. 2004), the last occurrence (LO) of *Triquetrorhabdulus rugosus* (5.28 Ma in Lourens et al. 2004); the LO *Discoaster quinqueramus* (5.54–5.58 Ma in Lourens et al. 2004); and the Marine Isotope Stage (MIS) TG5 global sea-level highstand.

No reliable calibrations were identified for these calcareous nannofossil events. This is partly due to the high degree of calcite dissolution associated with this time interval in Nordic Pliocene Zone NP0 (Diester-Haass et al. 2005). The siliceous bioevent MD6, marking the base of NP0, serves as a substitute marker in the Nordic region. The planktonic foraminiferal events PF12 (LO *Neogloboquadrina continuosa*) and PF13 (*Neogloboquadrina acostaensis*) are tentatively placed at this level, due to the high degree of diachroneity they show across latitudinal regions (Table 2).

4.3 Results: constraining the age of shallower deposits of the North Sea

The results of microscope analysis of a number of key Pliocene cores and an outcrop from the North Sea is presented in Table 3 and Figure 4. These currently represent the Pliocene North Sea sections with the best sample recovery. This exceptional recovery compared with other industrial drill cutting material has allowed for a greater degree of stratigraphic certainty. Located in the northern, central and southern North Sea, they offer a general stratigraphic and paleoenvironmental perspective of the basin during Early to mid-Pliocene time. The quality of data these sections afford has allowed second order calibrations between the North Sea benthic foraminiferal record and the high-resolution planktonic foraminiferal record of the Rockall Plateau (Fig. 3).

With the exception of Well 29/3-1, the deposits examined all appear to span relatively short stratigraphic time intervals within the Zanclean and possibly lowermost Piacenzian Stage. The age ranges deduced for the studied intervals are based on comparison of the isolated foraminiferal biofacies successions with the more extensive record of Well 29/3-1, together with identification of planktonic marker taxa with calibrated ages according to this study (Table 2). Where available, published dinoflagellate cyst events helped to further constrain the studied intervals (Fig. 4). Detailed foraminiferal and bolboformid counts are available in Appendix 2.

4.4 Results: North Sea foraminiferal correlations and updated age assignments

Correlation of the Nordic Pliocene Zonation with existing North Sea foraminiferal zonations is shown in Fig. 5. This has been achieved primarily through ties to the high-resolution planktonic foraminiferal record of the Rockall Plateau (Fig. 3). These correlations between planktonic and benthic foraminiferal events and zones have been identified both from the cores and outcrop in this study, and from published fossil occurrence data for the North Sea and offshore Mid-Norway. For certain intervals devoid of planktonic foraminifera, dinoflagellate cyst and bolboformid events help to constrain the benthic foraminiferal biostratigraphy.

4.4.1 Southern North Sea

The Dutch benthic foraminiferal zonation of Doppert (1979) describes three (sub)zones spanning the Lower to mid-Pliocene. The FC1/FB (sub)zonal boundary is characterised by the last common occurrence of *Uvigerina venusta (hosiusi) deurnensis*, equivalent to **BF4**. This suggests that the uppermost Breda Formation in the Netherlands may be as young as the Early Pliocene. This interpretation is supported by the late Early to early Late Pliocene age assignment of the uppermost Breda Formation by Bosch and Wesselingh (2006). They concluded on the basis of mollusc results that the top of the Breda Formation is probably time transgressive. This would explain the Tortonian age for the top Breda on the basis of dinoflagellate cysts in Wijnker et al. (2008). Doppert et al. (1979) correlated the Dutch FB/FC1 (sub)zonal boundary to the Belgian BFN4/BFN5 boundary of de Meuter and Laga (1976). De Meuter and Laga based their zonation on a study of the Kattendijk Formation. This formation has been dated by Louwye et al. (2004) to between ca. 5–4.4 Ma, being older than the dinoflagellate event **DC15** and younger than **DC16** and the FO *Ataxodinium confusum*. The latter occurs at the top of nannoplankton Zone NN12 (5.12 Ma) in the Italian Singa Section (Versteegh and Zevenboom 1995). Spiegler (2001) placed the Kattendijk Formation within the Lower *Bolboforma costairregularis* Zone. The Kattendijk Formation and associated benthos is therefore older than **BO4** at 4.36 Ma. The Belgian dinoflagellate study of Louwye et al. (2004) interpreted a hiatus between the Kattendijk and Lillo formations. Dating of the Coralline Crag Formation (This study, Head 1997, Jenkins et al. 1988) suggests an age for the base of the Coralline Crag Formation (3.8–4.3 Ma) similar to the base of the Lillo Formation ("Basal Shelly Unit") in Louwye et al. 2004. They assigned this level an age of ca. 4.2 Ma in the Netherlands, based on the absence of **DC5** and **DC9**. Note that **DC5** may be as young as 3.6 Ma and **DC9** is ca. 4.0 Ma (Table 2). The hiatus before deposition of the Coralline Crag Formation is inferred from the unconformity separating the underlying Eocene London Clay Formation (Head 1997).

In the Netherlands the FB/FA2 (sub)zonal boundary is equivalent to **BF2** (FO *Elphidiella hannai*; Top acme *Bulimina aculeata*/*marginata* group). This was magnetostratigraphically calibrated to ca. 3.2 Ma in Kuhlmann (2004). The same level was identified in Belgium as the BFN5/BFN6 zonal boundary. Here it also marks the top of an acme of *Cibicides lobatulus*. A similar assemblage was indentified in the Sudbourne Member of the Coralline Crag Formation of southeast England as "Facies B and C" (Hodgson and Funnell 1987). The foraminiferal assemblage of the overlying Red Crag is comparable to the upper part of the Lillo Formation with common *Elphidiella hannai* and consistently present *Neogloboquadrina atlantica* (sinistral coiled) (Gibbard et al. 1991). Spiegler (2001) identified the Upper *Bolboforma costairregularis* Zone in the Oorderen Member (Lillo Formation), further constraining the BFN5/BFN6 boundary to being older than **BO1**, at 2.93 Ma.

4.4.2 Central North Sea

In the central North Sea foraminiferal study of Eidvin and Riis (1995) and Eidvin et al. (1999) **PF13** is bracketed by two almost barren intervals in Well 2/4-C-11. **PF11** occurs within their planktonic *Neogloboquadrina acostaensis* assemblage (CE-FP) and within their benthic *Uvigerina venusta saxonica* assemblage (CE-GB). **PF10** occurs at their planktonic *Neogloboquadrina acostaensis*/*N. atlantica (dex)* (CE-FP/CE-EP) assemblage boundary and within their *Uvigerina venusta saxonica* assemblage (CE-GB). PF9 occurs together with **BF4** at the boundary between their *Uvigerina venusta saxonica* assemblage (CE-GB) and their *Monspeliensina pseudotepida – Cibicidoides limbatosuturalis* assemblage (CE-FB) and within their planktonic *Globigerina bulloides – N. atlantica* (sin) assemblage (CE-DP). **PF5** and **BF3** occur at the boundary between the planktonic assemblages CE-DP and *Globigerina bulloides* (CE-CP), and at the benthic assemblage boundary between CE-FB and *Monspeliensina pseudotepida* (CE-EB). **PF4** occurs at the planktonic assemblage boundary between CE-CP and the *N. pachyderma* (dex) assemblage (CE-BP), within the benthic CE-EB assemblage. **PF4** is overlain by a significantly less abundant and diverse fauna, almost devoid of a planktonic component. Slightly above this level is **BF2** (as the first consistent occurrence of *Elphidiella hannai*). This coincides with the planktonic CE-BP and the benthic CE-EB assemblages. **BF1** marks an increase in the benthic fauna, near the boundary between CE-EB and the *Cibicides grossus* assemblage (CE-DB). The overlying **PF1** event marks a reappearance of a consistent planktonic fauna, within the assemblages CE-BP and CE-DB of Eidvin and Riis (1995).

Table 3 Biostratigraphic and paleoenvironmental results for the studied North Sea wells and outcrop.

Region	Well/Outcrop	Age (Ma)	Constraining events
Northern North Sea	34/8-A-1H	4.5–4.2	Younger than the planktonic foraminiferal event PF9, and probably older than PF5. The presence of trace numbers of *Neogloboquadrina continuosa* may be reworked, but if not, place this assemblage nearer to PF5. The warm paleoenvironment and the absence of *Bolboforma costairregularis costairregularis* suggests an age for this assemblage older than the influx of the cool temperate flora at 4.2 Ma (Fig. 2), and therefore within Nordic Pliocene Zone NP2. The benthic foraminiferal assemblage supports this age range, being older than BF2 and falling between BF3 and BF4.
Northern North Sea	29/3-1	7.7–2.3	Interval from the planktonic event PF1, LO *Neogloboquadrina atlantica* (s), (2.3 Ma in Anthonissen 2008) to the LO *Bolboforma metzmacheri* (7.7 Ma in Spiegler 1999).
Northern North Sea	15/9-A-23	4.5–4.2	Younger than the planktonic foraminiferal bioevents PF8 and PF9 and older than the dinoflagellate cyst event DC10. The latter event was observed in Piasecki et al. (2002). They also recorded the presence of *Reticulatosphaera actinocoronata*, but noted that it it may have been reworked. This interpretation is supported by this study. The benthic foraminiferal assemblage is comparable to that of the lower part of the Ramsholt Member (Coralline Crag Formation) in southeast England. This suggests a placement at a level between benthic foramini-feral bioevents BF3 and BF4.
Central North Sea	16/1-1		Younger than planktonic foraminiferal bioevent PF9. Older than LO common *Bolboforma* cysts (4.4 Ma at ODP Site 982). Either the first or the second G. puncticulata Acme. Abundant *Uvigerina venusta* group and common *Nodosariidae* suggests an age no younger than BF4.

Table 3 Biostratigraphic and paleoenvironmental results for the studied North Sea wells and outcrop

NP Zone	Paleoenvironment	Comments
NP2 (–NP3)	The planktonic foraminiferal component, while recording low individual species abundance (except *N. atlantica* [sinistral coiled]), shows a relatively high diversity. The presence of *Beella praedigitata*, *Streptochilus sp*., *Globorotalia ex gr. scitula*, *Orbulina universa*, *Globigerina uvula* and *G. falconensis* point to a warm-temperate paleoclimate (Kennett and Srinivasan 1983). The diverse planktonic component, abundant *Sigmoilopsis schlumbergeri*, and the general absence of shallow neritic taxa suggest an upper bathyal paleodepth. The presence of the bathyal agglutinated taxa *Reticulophragmium rotundidorsatum* and *R. acutidorsatum*, although well-preserved, are sparsely present and therefore most probably reworked from Miocene sediments.	The benthic foraminiferal component compares to a similar level in Well 29/3–1.
Messinian + NP0–NP6	A paleobathymetrical interpretation, based on combination of planktic/benthic ratio (P/B ratio) and relative abundance of main foraminiferal wall-structure groups, suggests a trend from a Late Miocene upper bathyal paleodepth to an outer to middle neritic Pliocene paleodepth.	
NP2	The dominant faunal component is a shallower neritic one comprising: *Cassidulina laevigata, Cibicides lobatulus var, grossa, Nonion boueanum, Elphidium advenum* and *Spiroplectammina sagittula* group. While the common occurrence of *Pullenia bulloides* and *Oridorsalis umbonatus*, together with members of the Suborder Lagenina (*Lenticulina rotulata* and members of the Nodosariidae) would suggest a lower neritic to upper bathyal paleoenvironment (van Morkhoven et al. 1986, Gradstein and Backstrom 1996, Murray 2006), these species occur only sparsely in the samples analysed. *Pullenia bulloides* is also known to be a minor component of shallower shelf settings such as the Skagerrak Strait in the North Sea (Murray 2006). The juxtaposition of a shallow and a deep assemblage suggests significant downslope transport or reworking of older sediments. The general poor preservation of *Oridorsalis umbonatus* and large percentage of reworked planktonic species favours the reworking hypothesis. A middle to outer shelf paleoenvironment was the interpretation of Wilkinson 2000, based on foraminiferal and ostracod analysis of a single sample.	Wilkinson (2000) studies one sample from this core and reported similar foraminiferal findings.
Near NP1/NP2 boundary	The common occurrence of the benthic foraminifera *Pullenia bulloides*, *Oridorsalis umbonatus*, together with members of the Suborder Lagenina (*Lenticulina rotulata* and members of the Nodosariidae), suggests a lower neritic to upper bathyal paleoenvironment (van Morkhoven et al. 1986, Gradstein and Backstrom 1996, Murray 2006). The common occurrence of *Planulina ariminensis*, living in the Mediterranean at present, together with abundant planktonic *Globorotalia puncticulata* and rare *Orbulina universa* suggests a warm-temperate climate. This is supported by the common occurrence of high organic carbon-flux indicators such as *Bulimina aculeata, Melonis ex gr. barleeanus* and *Uvigerina venusta* group (Murray 2006).	The presence of Neogloboquadrina atlantica (d) is probably reworked from the underlying zone where this species has a brief influx.

Table 3 continued

Region	Well/Outcrop	Age (Ma)	Constraining events
Central North Sea	Rockhall Wood Outcrop (Coralline Crag Formation, Ramsholt Member)	3.6–3.8 (4.3)	Older than the planktonic foraminiferal event PF5 and older than the calcareous nannofossil LO *Sphenolithus* spp. (Jenkins and Houghton 1988). Younger than the bolboformid event BO3 (Jenkins and Houghton 1988) and containing the dinoflagellate cyst event DC8 (Head 1997). These results compare well with previous studies of the planktonic foraminifera from the Coralline Crag (see Jenkins et al. 1988).

4.4.3 Northern North Sea

In the northern North Sea correlations follow the foraminiferal core analysis in this study. Seidenkrantz (1992) erected a series of assemblages for three boreholes from the Gullfaks field (northern Viking Graben). The benthic foraminiferal event **BF2** was identified as the last common occurrence of *Textularia decrescens* (top of lower *Textularia decrescens – Spiroplectammina deperdita* (= *sagittula* group) assemblage) and the FO *Elphidiella hannai*. This level also coincided with the first occurrence of ice-rafted debris (IRD) and was interpreted as coinciding with the Lower/Upper Pliocene boundary. Eidvin et al. 2000 investigated a number of wells from the Snorre and Visund fields (northern Viking Graben). They concluded that most of the Lower Pliocene is absent from the northern North Sea. Only a brief interval representing the basal Lower Pliocene was identified as the uppermost part of the *Ehrenbergina variabilis* (NC-1) and the *Cibicidoides dutemplei* (NC-2) assemblages. Both the study by Seidenkrantz (1992) and the analysis of cored well 34/8-A-1H (This study) contradict this interpretation. This hiatus may therefore represent poor sample quality, a local unconformity or be a result of calcite dissolution as observed in the Northeastern Atlantic at this level (Diester-Haass et al. 2005).

Eidvin and Rundberg (2007) defined three benthic and three planktonic assemblages for the Lower to mid-Pliocene, based on a suite of eight industrial wells from the southern Viking Graben. These assemblages are underlain by a near-barren interval ("undefined interval" B1 and P3) assigned to the Utsira 'member' in Well 16/1-4. This may represent more than a lithofacies shift, as observed in the northern Viking Graben and Northeastern Atlantic. A *Globorotalia puncticulata* assemblage overlies this near-barren interval. The base is equivalent to **PF13**. The top is defined as the highest occurrence of *G. puncticulata*, but is here equivalent to the disappearance of *G. puncticulata* (**PF5**).Supporting this interpretation, **PF5** occurs at or near the benthic foraminiferal event **BF3**, marking the top of the *Uvigerina venusta saxonica* assemblage (Wells 25/10-2, 24/12–1, 16/1-4). Overlying these assemblages Eidvin and Rundberg (2007) described a planktonic *Neogloboquadrina atlantica* (sinistral coiled) assemblage and a benthic *Monspeliensina pseudotepida* assemblage (their *Globocassidulina subglobosa* assemblage, based on a single well, is considered time equivalent with the uppermost *U. venusta saxonica* assemblage). The top of these assemblages coincides with **PF1** and **BF1** respectively. The youngest planktonic assemblage to span the Lower to mid-Pliocene in the southern Viking Graben, according to Eidvin and Rundberg (2007), is their *Globigerina bulloides* assemblage. They defined the base as marked by either the LO *N. atlantica* (sinistral) (= **PF1**) or their LO *G. puncticulata* (= **PF5**) and the top by the LO *G. bulloides*. The authors consider this assemblage to be equivalent to the *G. bulloides* Zone of Weaver and Clement (1986). This is clearly only true for the first definition. The high-resolution plank-

NP Zone	Paleoenvironment	Comments
NP3	Recent benthic foraminiferal assemblages containing abundant *Cassidulina lævigata* and *Cibicides lobatulus* are indicative of a high-energy boreal shelf environment bathed in warm Atlantic water. A relatively high abundance of *Elphidium advenum* and *Nonion boueanum* are typical of an inner shelf setting (Murray 2006). The benthic foraminiferal assemblage of the Coralline Crag Formation was interpreted as indicative of an upper neritic paleoenvironment by Hodgson and Funnel (1987). The dominant interpretation of paleo- water temperatures is warm-temperate conditions, considerably higher than the present (Head 1997). The presence of the planktonic foraminifera *Neogloboquadrina atlantica* (sinistral coiled) and *Globorotalia puncticulata* suggests the presence of a marine connection through the English Channel to the North Atlantic, at least between 3.75–2.5 Ma (Funnell 1996). Lithologically, the Coralline Crag Formation may represent a tidal sand ridge complex (Balson 1989).	The benthic foraminiferal assemblage is similar to that of Well 15/9-A-23.

tonic foraminiferal record of the Rockall Plateau (Fig. 3) records the presence of the *G. bulloides* Zone of Weaver and Clement (1986) from 2.2–2.0 Ma. However, it also shows the presence of a *G. bulloides* dominated interval between **PF5** and **PF4,** from 3.6–3.3 Ma. The *Globigerina bulloides* assemblage of Eidvin and Rundberg (2007) is therefore ambiguous and represents at least two separate stratigraphic intervals.

4.4.4 Offshore Mid-Norway

On the continental shelf of Mid-Norway, Eidvin et al. (2007) interpreted a hiatus between ca. 5–4 Ma until the late Late Pliocene. The base of this eroded interval ranges from 4.6–3.1 Ma, based on the bracketing events **DC15** and **PF3c** in wells 6407/9-5 and 6507/12-1 (Fig. 5). The underlying Lower Pliocene sediment was assigned to the uppermost Molo 'member' in the Draugen Field (e. g. Well 6407/9-5), and to the Kai Formation at the more distal locations (e. g. Wells 6507/12-1 and 6508/5-1). Eidvin et al. (2007) described a basal Pliocene *Monspeliensina pseudotepida* assemblage coinciding with the LO *Bolboforma metzmacheri* (7.7 Ma on the Rockall Plateau in Spiegler 1999). Strontium isotope ratios gave an age of 5.2–5.8 Ma for this level. **PF13** may coincide with this level, as observed in Well 6508/5–1. Where the *M. pseudotepida* assemblage is absent (e. g. Well 6507/12–1), the Miocene/Pliocene boundary was interpreted as the top of a *Uvigerina venusta saxonica* assemblage. The boundary between the *Monspeliensina pseudotepida* (or *Uvigerina venusta saxonica*) assemblage and the overlying *Eponides pygmaeus – Cibicides telegdi* assemblage occurs above **PF10** (Influx of *N. atlantica* (d); Top dominant *G. bulloides*; Disappearance *Turborotalita quinqueloba* and *Globigerinita glutinata*).This boundary also occurs slightly below **DC15** (Well 6407/9–5), suggesting a correlation with the **BF4** event. The presence of an overlying erosional acuity may be observed as a depressed **BF3** event, due to the truncation of stratigraphic ranges (Fig. 5). The boundary between the *Eponides pygmaeus – Cibicides telegdi* assemblage and the *Eponides pygmaeus* assemblage is equivalent to **BF2**, occurring slightly older than **PF3c**.

4.4.5. Regional zonations

Based on the above correlations to the Nordic Pliocene Zonation, the ages of the zonal boundaries of King (1983, 1989) and Gradstein and Backstrom (1996) have been updated (Fig. 5). Due to lack of reliable tie points, the zonal boundary NSB14a/NSB14b of King (1983, 1989) is tentatively placed at the **BF2** level. The NSR11/NSR12A boundary of Gradstein and Backstrom (1996) was defined as the average last occurrence of *Globorotalia puncticulata* and *G. crassaformis*. Re-examination of the type interval for the NSR11 Zone (Well 16/1–1) revealed the presence of only *Globorotalia puncticulata* and a kummerform variety, similar to *G. puncticuloides*. The latter resembles *G. crassaformis hessi* in having a low aperture and a fairly robust, heavily calcified test. The authors correlated this zone with the *Globorotalia puncticulata*

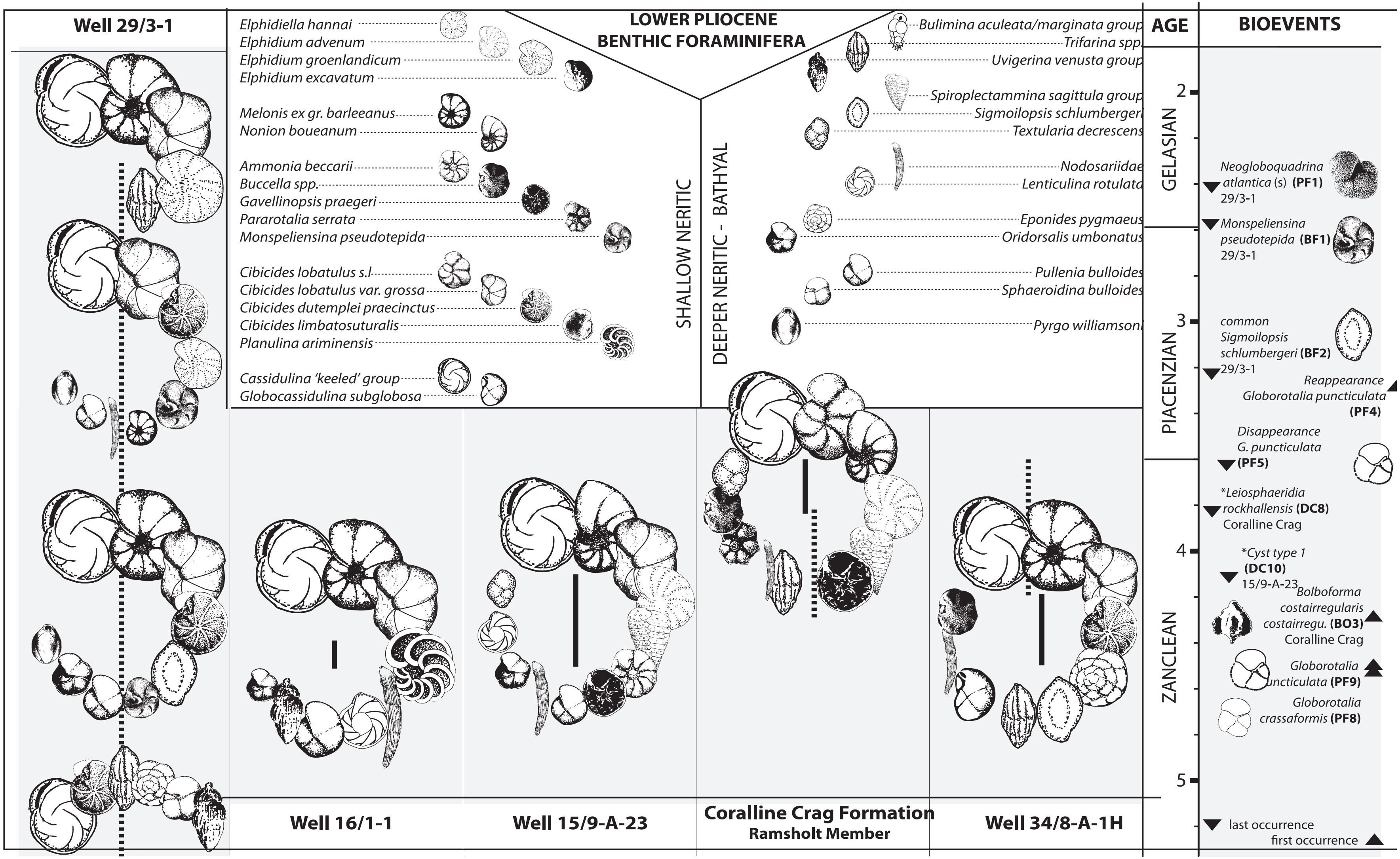


Fig. 4. Lower to Mid-Pliocene foraminiferal biofacies of analysed cores and outcrops in the North Sea region. The stratigraphic ranges of these neritic successions are constrained by the age-calibrated bioevents in this study (Table 2; Appendix 1). The image size of the benthic foraminiferal species is roughly proportional to their observed relative abundance. Age-constraining calcareous bioevents (planktonic foraminifera and bolboforms) are according to microscope observations in this study. Asterisks indicate palynological bioevents as observed by Piasecki et al. (2002) (Well 15/9-A-23) and Head (1997) (Coralline Crag). Ages are in millions of years with chronostratigraphy according to the time scale of Gradstein et al. (2004).

Zone of Weaver and Clement (1986). However, the marker for the top of this zone, LO *G.cf. crassula* (3.1 Ma), was not observed. The LO *G.puncticulata* occurs much later in the Nordic Atlantic region (2.4 Ma in Anthonissen 2008). The NSR11/NSR12A boundary has therefore been redefined as the 'Disappearance' of *G.puncticulata* (**PF5**) and assigned an age of 3.2 Ma (Fig. 5).

5. Paleoceanography, paleoclimate and global sequences

The Lower to mid-Pliocene succession of the Nordic region may be interpreted as a biotic and abiotic response to changing paleoceanography, paleoclimate and sea-level. This is shown in Fig. 2, where the new Nordic Pliocene Zonation is correlated with published paleoceanographic and paleoclimatic results.

First order calibrations of the Nordic Pliocene Zonation to the marine oxygen isotope record allowed for direct correlation to changing global sea-ice volume and paleoclimate. This correlation was achieved primarily through comparison of published North Atlantic paleoclimatic and paleoceanographic interpretations with the high-resolution planktonic foraminiferal and oxygen isotope record of the Rockall Plateau (Fig. 3). A Pliocene succession of warm- and cool-temperate assemblages was interpreted based on current distributions of living taxa, together with previous studies (see Ehrmann and Keigwin 1987; Keller et al. 1989; Kennett and Srinivasan 1983; Spezzaferri 1998). Tentative correlations to the global sequences of Hardenbol et al. (1998) are shown in Fig. 2. Their chronostratigraphic assignment is according to the update of Ogg and Lugowski (TSCreator 2008).

The base of the Pliocene and Nordic Pliocene Zone NP0 at ~ 5.3 Ma is marked by the last common occurrence of the subtropical planktonic foraminifer *Neogloboquadrina acostaensis*. This coincides with an increase in biogenic silica. A period of calcite dissolution followed, marking a shift from calcareous to siliceous dominated sediments (Diester-Haass et al. 2005). Relatively high oxygen isotope ratios and poor calcite preservation characterised the ensuing cold period until 4.8 Ma. The end of this cold period was marked by a shift to lighter oxygen isotope values and an increase in planktonic foraminiferal abundance. This level also marks a shift back to calcareous dominated sediments and the base of NP1 Zone. The first acme of *Orbulina universa* and *Neogloboquadrina atlantica* (sinistral) characterizes the cool temperate planktonic foraminiferal assemblages of this zone. The base of NP2 Zone at 4.5 Ma is marked by the first occurrence of a warm temperate planktonic foraminiferal assemblage with *Globorotalia puncticulata*. This appears to coincide with or immediately follow the initial closure of the Panamanian Seaway and associated strengthening of the Gulf Stream (Haug and Tiedemann 1998, Keller et al. 1989, Knappertsbusch 2007). The influx of a cold-adapted dinoflagellate (Head 1997) and bolboformid flora at 4.3–4.2 Ma defines the base of the NP3 Zone. This, together with the continued presence of a warm temperate planktonic foraminiferal fauna, suggests only a slight cooling trend. The base of NP4 Zone at 3.6 Ma is characterised by an increase in the planktonic foraminiferal upwelling species *Globigerinella aequilateralis* and *Globigerina bulloides* (Keller et al. 1989) and the disappearance of the warm temperate species *Globorotalia puncticulata*. This cooling trend coincides with an increase in oxygen isotope ratios and may be related to the first maximum in thermohaline overturn in the North Atlantic, as described in Haug and Tiedemann (1998). The termination of the ensuing cold interval or "failed initiation of Northern Hemisphere Glaciation" was marked by a decrease in the planktonic foraminiferal upwelling fauna and a reappearance of the warm temperate species *Globorotalia puncticulata* at 3.3 Ma. A significant shift towards lighter oxygen isotope values followed between 3.25–3.05 Ma with the Pliocene climatic optimum of Mudelsee and Raymo (2005). This warm period is believed to have been warmer than the present day with a brief pulse of subtropical planktonic foraminifers occurring as far north as the Arctic Ocean (Spiegler 1996). The last occurrence of this subtropical fauna at 3.1 Ma marks the end of this warm period and the base of NP5 Zone. The warm temperate planktonic foraminiferal fauna characterises this zone until its last common occurrence at 2.8–2.7 Ma at the base of NP6 Zone. This coincides with the final onset of Northern Hemisphere Glaciation (NHG) in the Nordic Atlantic region (Fronval and Jansen 1996, Haug and Tiedemann 1998, Knies et al. 2002, Mudelsee and Raymo 2005).

A strengthening of the Gulf Stream due to closure of the Panamanian Seaway may have provided the moisture required for the formation of continental glaciers in the northern high-latitudes (Haug and Tiedemann 1998). This step-wise cooling of Northern Hemisphere

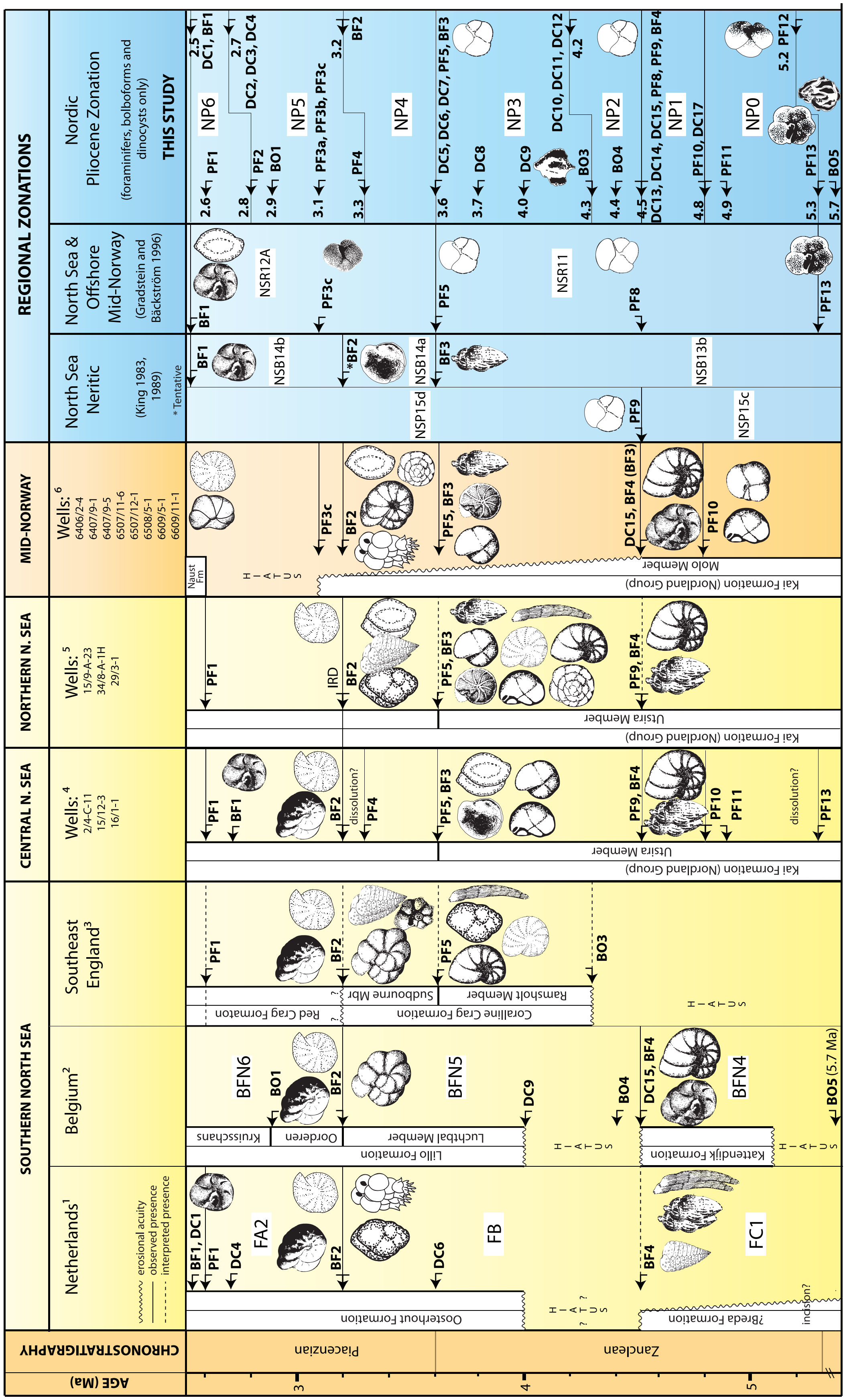

AGE (Ma)
CHRONOSTRATIGRAPHY
Piacenzian
Zanclean
SOUTHERN NORTH SEA
Netherlands[1]
erosional acuity
observed presence
interpreted presence
Oosterhout Formation
?Breda Formation
FA2
FB
FC1
Belgium[2]
Lillo Formation
Kruisschans
Oorderen
Luchtbal Member
Kattendijk Formation
BFN6
BFN5
BFN4
BO5 (5.7 Ma)
Southeast England[3]
Red Crag Formation
Coralline Crag Formation
Sudbourne Mbr
Ramsholt Member
CENTRAL N. SEA
Wells: [4]
2/4-C-11
15/12-3
16/1-1
Kai Formation (Nordland Group)
Utsira Member
NORTHERN N. SEA
Wells: [5]
15/9-A-23
34/8-A-1H
29/3-1
MID-NORWAY
Wells: [6]
6406/2-4
6407/9-1
6407/9-5
6507/11-6
6507/12-1
6508/5-1
6609/5-1
6609/11-1
Naust Fm
Molo Member
REGIONAL ZONATIONS
North Sea Neritic
(King 1983, 1989)
* Tentative
NSB14b
NSB14a
NSB13b
NSP15d
NSP15c
North Sea & Offshore Mid-Norway
(Gradstein and Bäckström 1996)
NSR12A
NSR11
Nordic Pliocene Zonation
(foraminifers, bolboforms and dinocysts only)
THIS STUDY
NP6
NP5
NP4
NP3
NP2
NP1
NP0

Fig. 5. A correlation of Lower to Mid-Pliocene foraminiferal zonations and assemblages from the southern North Sea to offshore Mid-Norway. The ages of zonal/assemblage boundaries are according to the new and updated age calibrations of zonal markers (bold) in this study. Bioevent codes (bold) are according to Table 2. For a key to the benthic foraminiferal illustrations see Fig. 4. Two superimposed illustrations signify a last common occurrence. Lithostratigraphy follows that of the Norwegian Interactive Offshore Stratigraphic Lexicon (Gradstein et al. in prep.) and Eidvin and Rundberg (2007). **References:** 1. Kuhlmann (2004), Doppert et al. (1979), Doppert (1980). 2. De Meuter and Laga (1976), Louwye et al. (2004). 3. This study (Coralline Crag, Ramsholt Mbr). 4. Eidvin and Riis (1995), This study (16/1–1). 5. Eidvin and Riis (1995), Seidenkrantz (1992), This study (15/9-A-23, 34/8-A-1H, 29/3–1). 6. Eidvin and Riis (1995), Eidvin et al. (2007). **Zones:** Netherlands (Doppert et al. 1979): FA2: *Buccella frigida* – *Cassidulina laevigata* Subzone, *Elphidiella hannai* – *Elphidium* (*Cribrononion*) *excavatum* Zone; FB: *Textularia decrescens* – *Bulimina aculeata* Zone; FC1: *Nodosariidae* (*Dentalina*) – *Cassidulina Subzone*, *Spiroplectammina* (*Siphotextularia*) *sculpturata* – *Uvigerina venusta deurnensis* (*hosiusi*) Zone. Belgium (de Meuter and Laga 1976): BFN6: *Elphidiella hannai* – *Elphidium* (*Cribrononion*) *excavatum* Zone; BFN5: *Cibicides lobatulus* Peak Zone; BFN4: *Nonion* (*Florilus*) *boueanum* (*boueanus*) – *Monspeliensina pseudotepida* Zone. Northern North Sea (Seidenkrantz 1992): *Elphidiella hannai* Assemblage, *Textularia decrescens* – *Spiroplectammina* (*deperdita*) *sagittula* – *Cibicides lobatulus* Assemblage. Regional Zonations (King 1983, 1989): NSP 15c: *Neogloboquadrina atlantica* (sinistral) Subzone; NSP15d: *Globorotalia puncticulata* Subzone; NSB13b: *Uvigerina venusta saxonica* Subzone; NSB14a: *Cibicidoides limbatosuturalis* Subzone; NSB14b: *Monspeliensina pseudotepida* Subzone. Regional Zonations (Gradstein and Backstrom 1996): NSR12A: *Globorotalia inflata* Zone; NSR11: *Neogloboquadrina atlantica* Zone.

climate, beginning with a series of cold periods or 'failed initiations' of Northern Hemisphere Glaciation and ending in the onset of NHG, appears to coincide with major turnover levels in the microfossil records of the Nordic region.

6. Conclusions

A new multifossil zonation for the Lower to mid-Pliocene of the Nordic Atlantic has been constructed, based mainly on Ocean Drilling data. Micropaleontological analysis of key Pliocene cored well intervals and outcrops in the North Sea region has resulted in a better constrained benthic foraminiferal biostratigraphy. The standard Pliocene GSSP correlative markers are only rarely present in Nordic high latitudes, and may show strong diachroneity as in the case of the last occurrence of the planktonic foraminifer *Globorotalia margaritae*. For the Nordic Atlantic region this zonation allows for easier identification of the standard global Stage boundaries of the Pliocene Series, with most zonal boundaries tied directly to the marine oxygen isotope record. The Lower to mid-Pliocene biostratigraphy of the Nordic Atlantic appears to represent a biotic response to intensification of the Gulf Stream with the closure of the Panamanian Seaway, and to the stepwise cooling and final initiation of the Northern Hemisphere Glaciation. The planktonic foraminiferal extinction events PF3a and PF3b, although rare, represent the last time a significant influx of a warm-temperate to subtropical planktonic foraminiferal fauna and dinoflagellate flora was present at such high latitudes in the Nordic region.

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Supporting data is available as Appendix 1 (Pliocene event calibrations) and Appendix 2 (Pliocene foraminiferal and bolboformid fossil counts) from http://www.norges.uio.no/norlex.

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